THE EFFECT OF MATERIAL PARAMETERS ON FRICTION AND WEAR

Ary Biolchini
Merwin Sacarob
and
Gabriel Francisco de Andrade Villela

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by

ARY BIOLCHINI
Brazilian Naval Academy (1945)

and

MERWIN SACAROB
B.S., U. S. Naval Academy (1949)

and

GABRIEL FRANCISCO DE ANDRADE VILLELA
Brazilian Naval Academy (1945)

SUBMITTED IN PARTIAL FULFILLMENT
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DEGREE OF NAVAL ENGINEER

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1956

Department of Naval Architecture
and Marine Engineering
May 21, 1956

Signature of Authors _____

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_____

Certified by: _____
Thesis Supervisor

Accepted by: _____
Chairman, Departmental
Committee on Graduate
Students

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Thesis
B5428

Cambridge, Massachusetts

May 21, 1956

Professor Leicester F. Hamilton,
Secretary of the Faculty,
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Hamilton:

In accordance with the requirements of the degree of Naval Engineer, we herewith submit a thesis entitled "The Effect of Material Parameters on Friction and Wear".

ABSTRACT

THE EFFECT OF MATERIAL PARAMETERS ON FRICTION AND WEAR

By

Ary Biolchini

Merwin Sacarob

Gabriel F. A. Villela

Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1956 in partial fulfillment of the requirements for the degree of Naval Engineer.

The object of this work was to discover the effect of hardness and heat treatment of steel on the friction and wear of this steel. That there was an effect had been conjectured for some time, but little or no work had been done in this field.

In brief, the procedure was very simple, rubbing hemispherical sliders of differing heat treatments and hardnesses against a much harder steel surface, and measuring the friction by means of a strain ring and Sanborn recorder, and measuring the wear by measuring the diameter of the wear spot and calculating the volume of the missing portion of the hemisphere.

The results show that there is a difference in both the wear and the friction, and that this difference depends upon the hardness and the heat treatment, although the difference is small. Friction increases with increasing hardness and with increasing hardening temperature, with the hardening temperature showing the greater influence. Wear decreases with increasing hardening temperature, and increases with increasing hardness.

There appears to be a small correlation between friction and wear, inasmuch as both friction and wear increase with increasing hardness, and with increasing hardening temperature friction increases and wear decreases, but these were not formulated. The friction coefficient increased for a slider as it ran over the same path because of the breakdown of the martensitic surface of the path under the extreme pressures and temperatures, bringing the structure of slider and path closer together. Adhesive wear turned out to be a linear function of the distance travelled, but when combined with corrosive wear, interactions were set up that made the wear non-linear.

It is recommended that future experiments should be conducted in an inert atmosphere so that the change of one surface due to the picking up of material from the other surface and to the decay of the martensite may be evaluated.

Thesis Supervisor: Brandon G. Rightmire
Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENT

We wish to acknowledge the aid of Professor Michael B. Bever, of the Metallurgy Department, in keeping us on the right road, metallurgically speaking, and Professor Brandon G. Rightmire, of the Department of Mechanical Engineering, whose aid and assistance was deemed incalculable.

TABLE OF CONTENTS

TITLE

ABSTRACT

ACKNOWLEDGEMENT

TABLE OF CONTENTS		Page
I.	INTRODUCTION	1
	A. Friction	1
	B. Wear	5
II.	PROCEDURE	10
	A. Preparation	10
	B. Friction	11
	C. Wear	12
III.	IDENTIFICATION OF SLIDERS	14
IV.	RESULTS	15
	A. Friction	15
	B. Wear	15
V.	DISCUSSION OF RESULTS	39
	A. Friction	39
	B. Wear	41
VI.	CONCLUSIONS	45
VII.	RECOMMENDATIONS	46
VIII.	APPENDIX	47
	A. Supplementary Introduction	48
	B. Sample Calculations	53
	C. Bibliography	55

I. INTRODUCTION

A) Friction

The friction forces observed when two metals slide on each other are dependent on so many variables that the effect of each variable must be determined separately by means of suitable experimentation, if possible. The results are then analyzed and compared with existing data, theories are tested, and then a theoretical explanation of the phenomena is attempted. However, the difficulties that must be overcome in the laboratory usually make it impossible to isolate the several influencing factors effectively; the interaction of effects tends to distort the desired results and the evaluation of the data obtained must be made with this in mind.

In this paper the authors have attempted to determine the influence of material parameters on the friction and wear of sliding metals. There are several theories extant that attempt to explain the process of friction and wear. Some involve only qualitative statements about the phenomena while others contain more or less extensive mathematical treatments based on assumed configurations of the interface, areas of contact, properties of the metals involved, oxide and liquid layers, etc.

There has been some disagreement as to the interdependence of frictional forces and surface damage. Some

authors state that there is a definite correlation between the friction and the wear effects, while others theorize that although both friction and wear are influenced by the same variables, their effects are of a different nature, and therefore there is no correlation between them. Another source of conflict lies in the influence of the properties of the metals. Several authors state that the individual properties such as hardness, melting point, etc., are significant, and in reference 2 we find that their absolute properties are unimportant, but the properties of one relative to those of the other are the commanding factors.

We might expect that the sliding of steel on steel would be characteristic of similar metals. However, because of the non-homogeneous microstructure of steel, small localized points of contact between the upper and the lower surface will not in general be of identical composition and physical properties, and therefore steel on steel might not act as similar metals will. (Reference 2)

The presence of the Beilby layer (reference 2) must be discussed here because both the disk and the sliders were given such a high degree of polish that the favorable conditions for the formation of this layer are certainly present. The highly martensitic structure of the disk is likely to become unstable at the surface due to the high local temperatures and pressures existing during the finishing process, and the Beilby layer that builds up on the surface must have a lower hardness than the bulk of the speci-

men. On the other hand, the very fine structure of the Beilby layer on the sliders tends to possess a greater hardness than the body of the material. The very first part of each run is therefore made between the Beilby layers of the slider and the disk, and the data taken must not be expected to represent the conditions for which the experiment has been devised. The structure in the Beilby layers is so refined that the behavior of the interface during this beginning must approach the condition of similar metals, and high values of friction force accompanied by considerable surface damage are to be expected; both of these phenomena will tend to consume the Beilby layers at a very fast rate, and therefore the effect described here will be washed out early in the test, if the test is allowed to run a sufficiently long time.

After both Beilby layers have been destroyed the friction forces are characteristic of the materials employed in the test, and are relatively insensitive to the initial degree of polishing. The very high hardness of the disk as compared with the sliders gives a high relative hardness and the behavior tends toward that of dissimilar metals. However, if the same track is used over and over, it is possible that the martensitic microstructure of the disk at the points of contact starts degenerating into a more stable configuration, but with a lower hardness. Since the slider maintains its properties, the relative hardness across the interface diminishes, resulting in higher friction forces and

surface damage.

The very short life of the Beilby layer has not been determined accurately due to the high speed of sliding that has been used in all experiments. However, the effect of gradual increase of the friction force with distance travelled was noted and will be discussed.

It is noted that there may also be an effect due to surface temperature on the properties of the sliding metals. Although very high temperatures are present at the points of contact, the speed of travel is great enough to keep the rate of deformation of the junctions at a very high value. From reference 16 pertaining to the creep of metals, we find that the continuous deformation of the bodies with time for a certain applied stress, produced by grain boundary sliding and migration, is a function of the rate of deformation imposed upon the body and also of its temperature as compared with the equicohesive temperature of the metal. An increase in the rate of deformation allows less time for the grain boundary sliding and migration phenomena to take place. Theoretically we can always increase the rate of deformation so as to keep the equicohesive temperature higher than a predetermined level; in this case the specimen will always rupture across the grains, a typical low-temperature behavior. The very high rates of deformation of the junctions in our experiments lead us to expect that the low-temperature properties of the metals can be used, and the mathematical treatments in references 2 and 15 may be applied

to our tests if necessary.

B) Wear

The process of wear is a complex process. Generally speaking it is not desired, but it happens. To illustrate its complexity, wear has been classified into five different types, which may appear singly or combined, depending on the particular instance. Any slight change in the operating conditions may change the entire nature of the wear process. These phenomena are quite distinct and independent of one another, having in common only the removal of solid material from the rubbing surfaces.

Burwell (reference 4) lists the five mechanisms of wear as 1) adhesive or galling wear, 2) abrasive or cutting wear, 3) corrosive wear, 4) surface fatigue, 5) minor types. Adhesive wear is the most fundamental of the several types of wear in the sense that it is a basic phenomenon that takes place whenever two solid surfaces are in rubbing contact, whether lubricated or not, and remains when all other types of wear are eliminated. This is caused by the welding of small points of contact of the surfaces and the subsequent tearing of the welds by the relative motion of the surfaces.

Abrasive wear is the removal of solid material from a surface by plowing or gouging it out by a much harder surface. This is also referred to as scoring. Abrasive wear was eliminated from the experiments carried on for this thesis

by polishing both surfaces to a relatively high degree, and by polishing in the direction of travel. Careful cleaning of the rubbing surfaces also helped in eliminating this.

Corrosive wear takes place when a corrosive environment produces a reaction product on one or both of the rubbing surfaces, and this reaction product is subsequently removed from the surface by the rubbing. This environment is most usually air at room temperature. Oxides are formed, and with few exceptions, they are loosely adherent to the metal base so that even the mildest rubbing serves to remove them. Where the slider is run over the same path, this oxide will tend to serve as a polishing agent, wearing down the softer material, since the oxide is generally of a high hardness. This is eliminated in the experiments utilizing a fresh path, since any oxide that is rubbed loose lies in place and is not touched by the slider which has moved to a fresh path.

Surface fatigue, according to Burwell, occurs only between two rolling surfaces. Since these experiments deal only with sliding surfaces, this type of wear is completely eliminated. Under minor types of wear Burwell lists particular cases such as that caused by high velocity liquids. All of these were avoided in our experiments.

In reference 2, the authors state that the welds mentioned above under adhesive wear will be work-hardened, and will therefore not fracture at the interface, but will fracture somewhere in the bulk of the material. For this

reason a cylinder of extreme hardness was obtained, so that the hardness of the welds would approach that of the cylinder, and the shearing would take place in the softer metal of the slider. Thus the much greater amount of wear would take place on the slider, with very little damage resulting on the cylinder. The sliders ranged in hardness from about 25 Rockwell C to nearly 60 Rockwell C.

For the harder sliders it was expected that the wear would be less than that of the softer sliders because the hardness of the bulk material in this case would be close to that of the cylinder and therefore the shearing of the welds would occur closer to or at the interface. It would appear as though the wear on the harder samples would not be too dependent on the grain size of the material.

In the softer sliders the influence of grain size, according to reference 2, would be felt to a greater degree. Since we have concluded previously that the wear is dependent on the work hardenability of the welded contact areas and work hardenability of steel is somewhat dependent on the grain size of the material, then we might expect to find a difference in wear between the softer samples. This may also show up to a lesser degree in the harder samples.

Bowden and Tabor arrive at the conclusion that there is no direct relationship between the coefficient of friction and the amount of wear. The amount of metal lost from the surface depends critically on the region within which shearing of the welded junction occurs. The friction forces,

on the other hand, may be essentially the same whether shearing occurs in the bulk of the metals or at the interface of contact.

Dies and others carried out experiments in Germany with steel surfaces sliding on a rotating hard steel disk, with no lubricant and at relatively high loads and speeds. They restricted their investigation to the field of abrasive wear. Dies found that with mild steel sliding on a hard chromium steel, the wear is considerably less than for mild steel on mild steel. As the load was increased, the wear at first increased, then rapidly fell, and finally rose again. The critical load at which the drop occurred is increased if the surfaces are cooled and is decreased if the speed is increased.

It was suggested that the decrease in wear is a real effect which corresponds to a transition from one type of wear process to another. The chemical action of the atmosphere surrounding the rubbing surfaces may be expected to play an important role on this critical load. It was observed that up to the critical load the surface hardness is somewhat greater than the bulk hardness, while beyond the critical load the surface hardness is very much greater. This marked increase was attributed partly to the formation from atmospheric nitrogen of nitrided layers which penetrated to an appreciable depth and partly to the distortion and work-hardening of the metal under the more severe conditions of operation. Oxide films formed by the rubbing surfaces were also noted.

By selecting a load of three hundred grams, we eliminated the possibility of falling within the critical range, where atmospheric conditions are also critical. We are operating well above the critical range where atmospheric conditions will have little effect. Dies showed that the critical load was about ten kilograms per square centimeter. We operated with loads on the order of two hundred and fifty kilograms per square centimeter. This assures that the same wear process is attained for all specimens.

II. PROCEDURE

A) Preparation

The sliders for both sets of experiments were prepared in the same manner. A hemispherical surface was ground on one end of the slider sample, a quarter inch steel dowel about one and one-quarter inches long. It was intended that the radius of this sphere be equal to that of the dowel, but this could not be made by a reproduceable process in the laboratory, so a perfect hemisphere with a radius between 0.115 and 0.140 inches was accepted. This surface was polished with 4/0 french polishing paper and the radius was then measured with the aid of a comparator, which magnified the shadow of the hemisphere 32.5X and threw the enlarged shadow on a ground glass screen on which were scribed concentric circles at intervals of 0.002 inches.

Both the cylinder, for the wear experiments, and the disk, for the friction experiments, were also polished to the highest degree necessary to give reliable results. The cylinder and the disk were both of the same material, oil-hardening tool steel, and both were heat treated to a hardness of 64 Rockwell C. The specimens used were of a special composition steel, containing 1.03% Carbon, 0.42% Manganese, 0.013% Phosphorus, 0.026% Sulphur, and 0.22% Silicon. The specimens were subjected to different heat treatments, so that there are two hardnesses represented, with each hardness being coupled with two different grain sizes.

B) Friction Experiments

The friction tests were made on an inverted drill press which was run by a controllable speed motor (see Figure I). The steel disk, five inches in diameter, was mounted on the drill press, so that it would be rotated. The slider was mounted in a friction arm which was positioned in such a way that the friction force was at right angles to the friction arm, that is, the friction arm was aligned with a radius of the disk, and the friction force thus compressed the strain ring on which were mounted two strain gages. The output of the strain gages was put into a Sanborn recorder, which had been calibrated previously by applying known forces in the direction of the friction force. Therefore the friction force could be read directly from the tape in the Sanborn recorder.

The slider was mounted, and a weight was applied to the top of the friction arm so as to bring a known normal load to the slider. The slider was mounted so as to be perpendicular to the plane of the disk. The disk speed was adjusted so that the speed of travel of the slider would remain at about thirty centimeters per second, regardless of the radius at which the slider moved. Thus the path could be changed for each specimen without necessitating frequent repolishing. This speed was selected because it proved to be one on which the fewest disturbances, such as stick-and-slip, and vibration, were encountered over most of the load range.

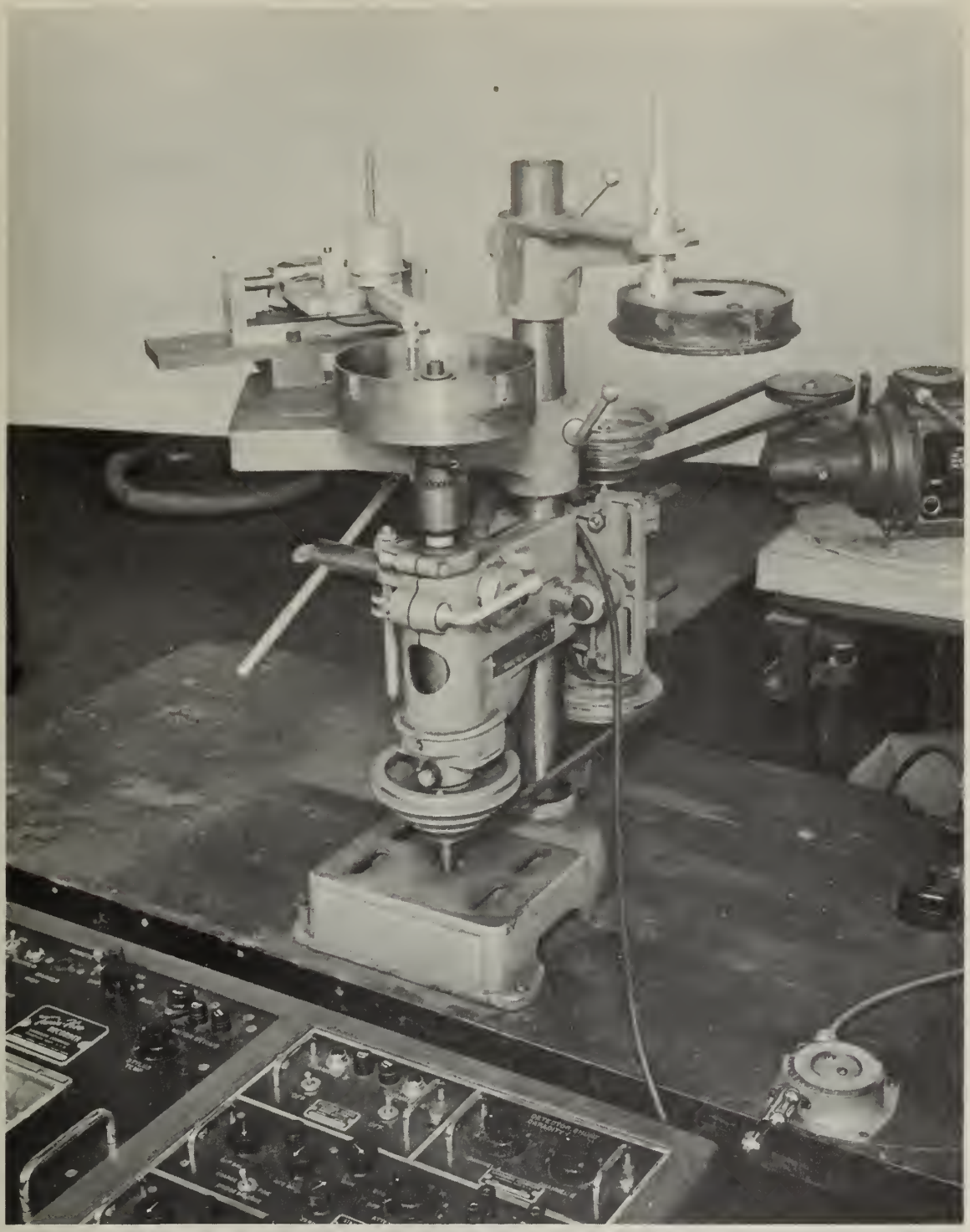


Figure I. Friction Test Machine

During the run with each sample normal loads varying from zero to three hundred grams were applied. The sample was allowed to run over the same path about ten times before data was taken so that the results would not be affected by any film on the metal.

C) Wear Experiments

The wear tests were run on a standard lathe (Figure II), using a rotating steel cylinder for the path of the slider. The cylinder was about five inches in diameter and twenty inches long. The slider was mounted in a friction arm built so that the friction force, tangent to the cylinder in a plane perpendicular to the centerline of the cylinder, could be measured. However, it was found that this arm was not rigid enough to give repeatable readings, and therefore, the readings obtained were not used.

The friction arm was mounted on the lathe carriage so that the slider could be made to move in a helical path on the cylinder. The slider was carefully set in the friction arm and marked so that its position could be reproduced if it were removed. A normal load of three hundred grams was maintained throughout the wear experiments.

For the slider to move on a fresh path, the carriage was set on automatic feed, and set to run at a horizontal rate of 0.003 inches per revolution. At this rate it was possible to run the slider over a track of about four hundred meters length and just about cover the entire surface

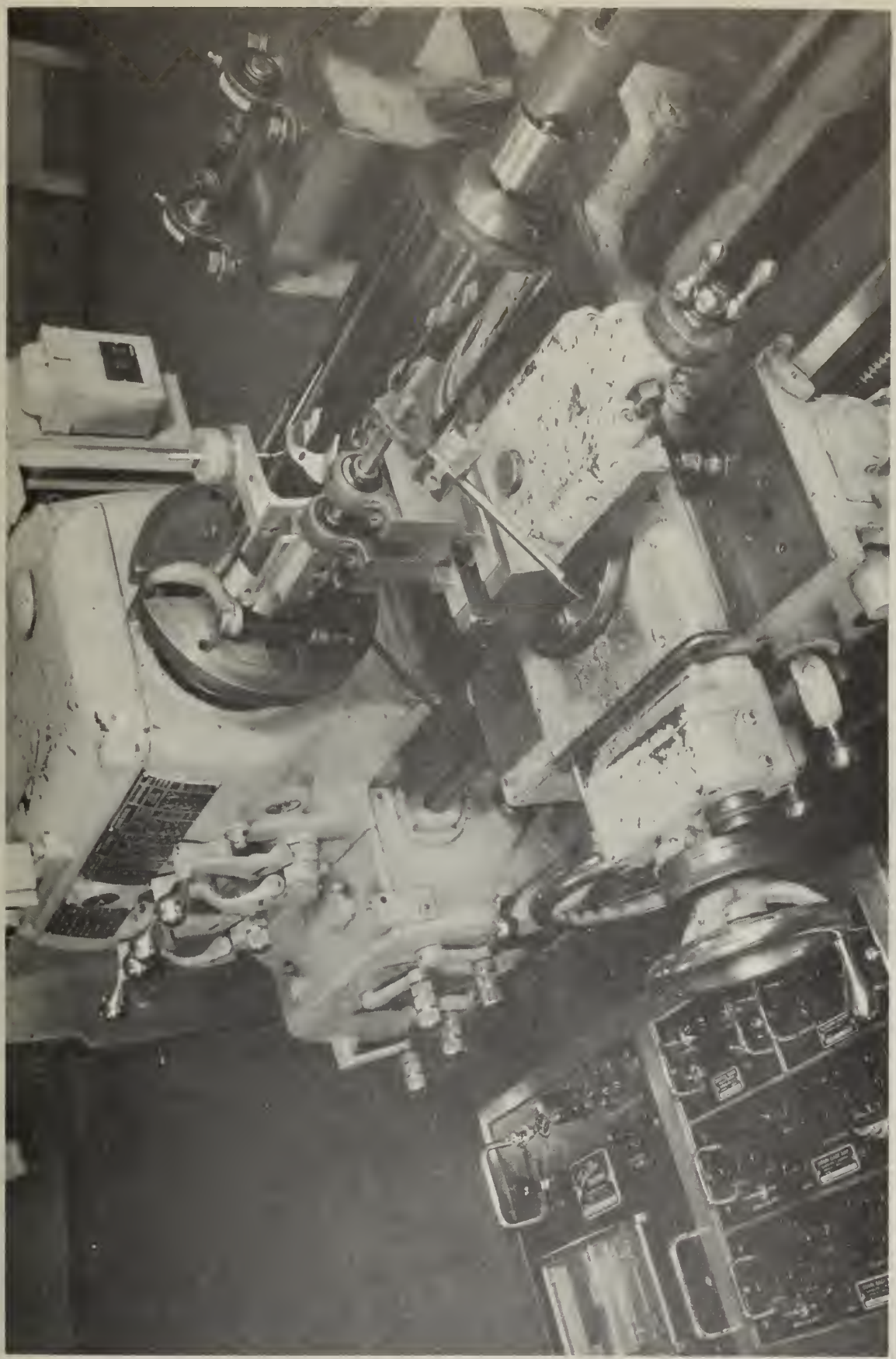


Figure II. Wear Test Machine

of the cylinder, so that it was necessary to repolish the cylinder before each run on a fresh path. Approximately eight hours work was required for each repolishing. Where the experiment called for the slider to run on the same path, the carriage remained in one position. The cylinder was rotated at 45 RPM, which produced a slider speed of 30.6 centimeters per second.

Every two hundred and forty revolutions, or a run of just under one hundred meters, the sample was removed and the point of contact was examined under a microscope (see Figures III - VI). The diameter of the wear spot was measured, and the slider was replaced in the arm, with care being taken to replace it exactly as it was. Then another hundred meters was run. The slider was removed and the diameter of the wear spot was measured after 100, 200, 300, and 400 meters. On the second run, measurements were taken after runs of 50, 150, 250, and 350 meters.

III. IDENTIFICATION OF SLIDERS

Originally it was intended that a comparison of the sliders as to friction and wear would be made on the basis of such parameters as hardness and grain size. The sliders did differ in hardness as indicated below, but unfortunately the size of the grain could not be distinguished due to the highly martensitic structure. This did not become apparent until after a sample of each type was mounted, polished, and etched with a suitable reagent. Therefore, instead of referring to the difference in grain size, we will refer to the heat treatment of the specimen.

Specimen	Hardening Temperature	Drawing Temperature	Hardness Range Rockwell C
A	1425°F	850°F	28 - 31
B	1650	850	28 - 30
C	1425	350	54 - 55
D	1650	350	55 - 58

All specimens were kept at the drawing temperature for one hour. The sliders will be referred to hereinafter by their letter designation.

IV. RESULTS

A) Friction

The results of the friction experiments are presented as graphs, Figures VII through XII. Figures VII through X present the plot of the friction force versus the normal load for sliders A, B, C, and D, respectively. Figures XI and XII are plots of the friction coefficients for the different sliders for short travel and for long travel.

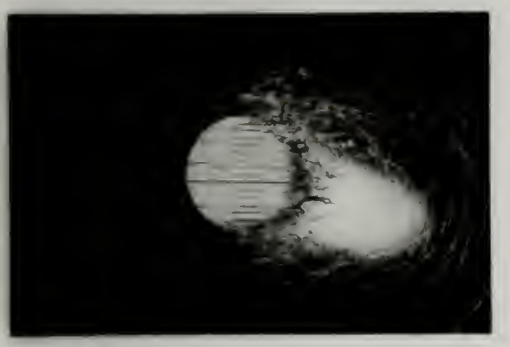
B) Wear

The results of the wear experiments are presented in graphical form, Figures XIII to XVIII. Figures XIII, XIV, XV, and XVI are the plots of the volume wear versus length of travel, both fresh path and same path, for specimens A, B, C, and D, respectively. In Figure XVII we have combined the fresh path plots of the sliders, taking the curves from the previous graphs, and in Figure XVIII we have combined the same plots in the same manner, to facilitate comparison of the curves.

Figures XIX through XXII are plots of volume wear versus distance travelled for the same specimens carrying a load of six hundred grams instead of three hundred grams. These were done in an attempt to explore Burwell's theory of wear being proportional to load times distance travelled.

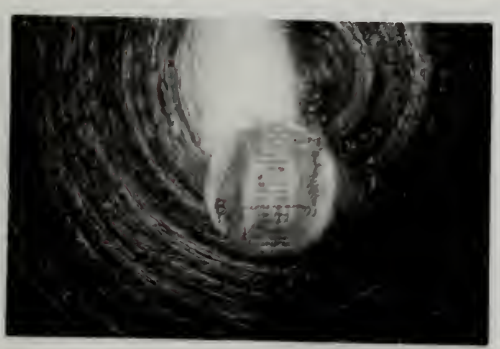
Figures XXIII and XXIV bring together all curves of same path and fresh path on this basis.

Figures III through VI show the relative size of the wear spot as seen through a microscope, magnified about 100X. On several of the photographs can be seen the scale used to measure the diameter of the wear spot.

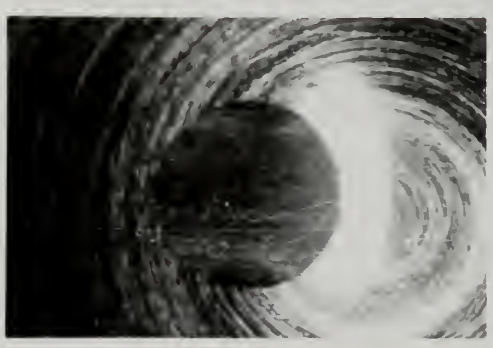


a. Fresh Path, after 50 Meters Travel

b. Fresh Path, after 150 Meters Travel



c. Same Path, after 50 Meters Travel

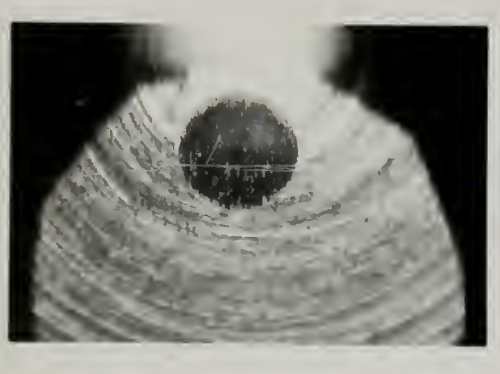


d. Same Path, after 150 Meters Travel

FIGURE III

MICROSCOPE PHOTOGRAPHS OF THE WEAR SPOT ON SPECIMEN A.

(About 100 x)



a. Fresh Path, after 50 Meters Travel

b. Fresh Path, after 150 Meters Travel

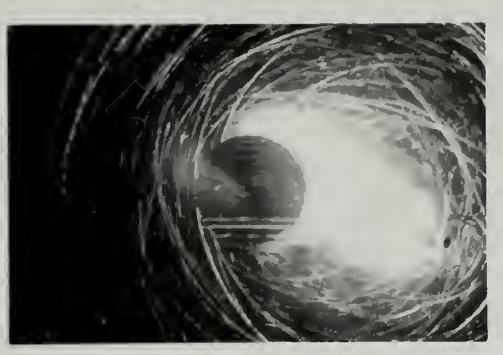
c. Same Path, after 50 Meters Travel

d. Same Path, after 150 Meters Travel

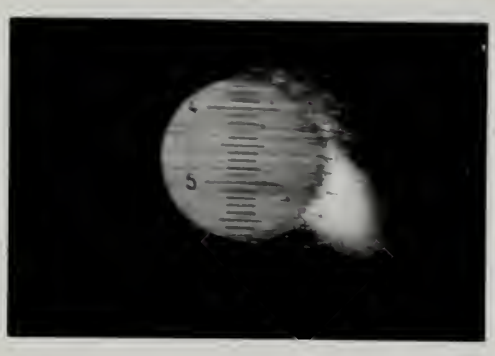
FIGURE IV

MICROSCOPE PHOTOGRAPHS OF THE WEAR SPOT ON SPECIMEN B.

(About 100X)

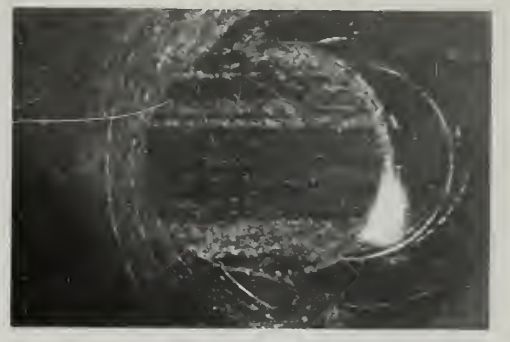


a. Fresh Path, after 50 Meters Travel



b. Fresh Path, after 150 Meters Travel

c. Same Path, after 50 Meters Travel



d. Same Path, after 150 Meters Travel

FIGURE V

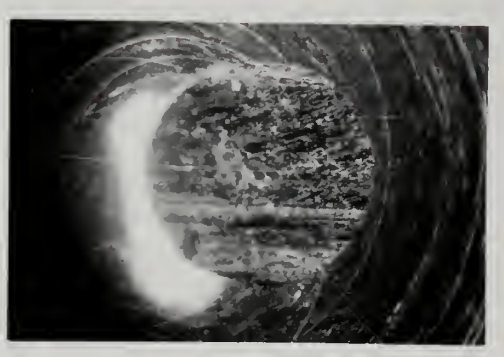
MICROSCOPE PHOTOGRAPHS OF THE WEAR SPOT ON SPECIMEN C.

(About 100 X)

a. Fresh Path, after 50 Meters Travel

b. Fresh Path, after 150 Meters Travel

c. Same Path, after 50 Meters Travel



d. Same Path, after 150 Meters Travel

FIGURE VI

MICROSCOPE PHOTOGRAPHS OF THE WEAR SPOT ON SPECIMEN D.

(About 100X)

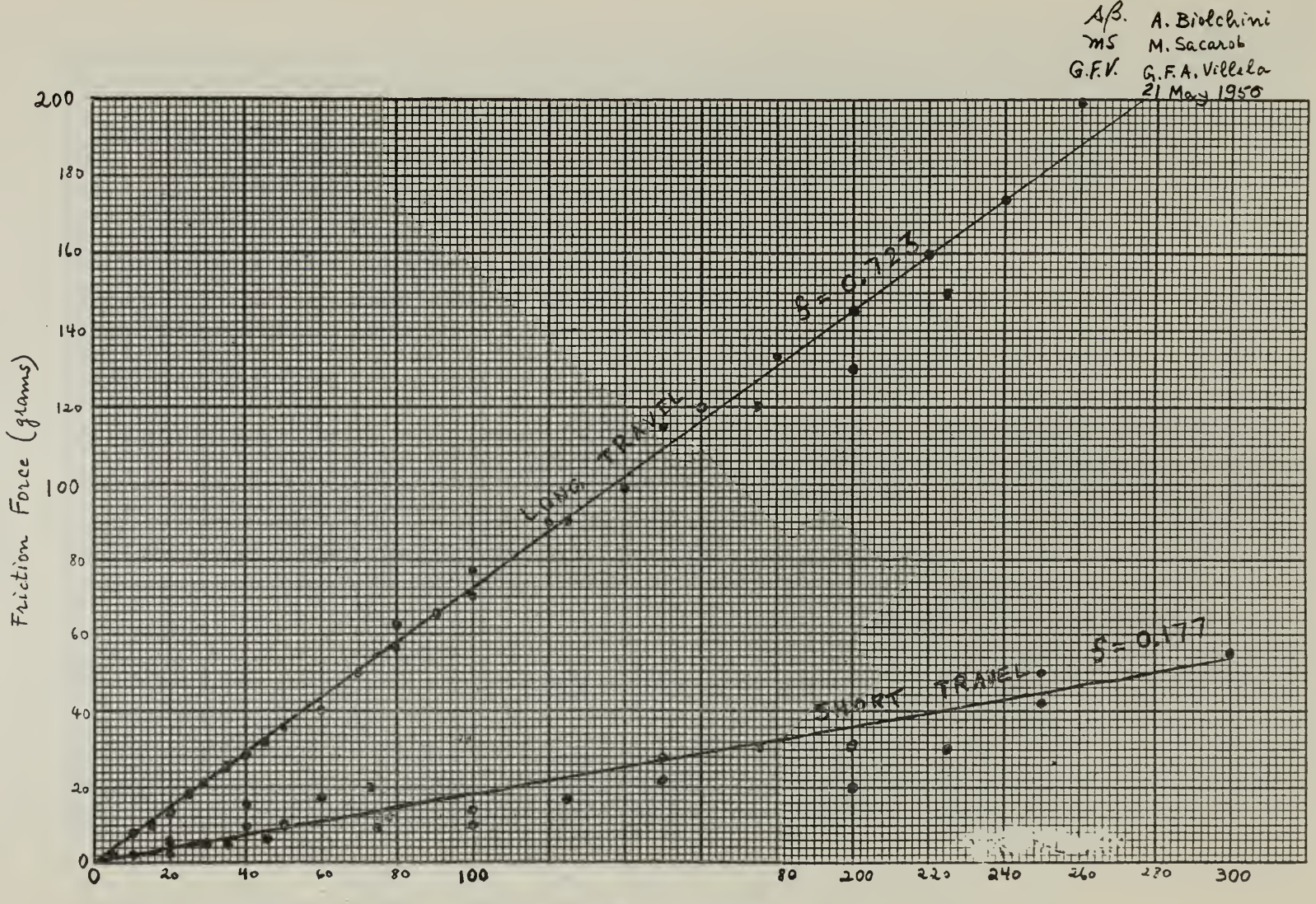


FIGURE VII.- FRICTION FORCES ON SPECIMEN A

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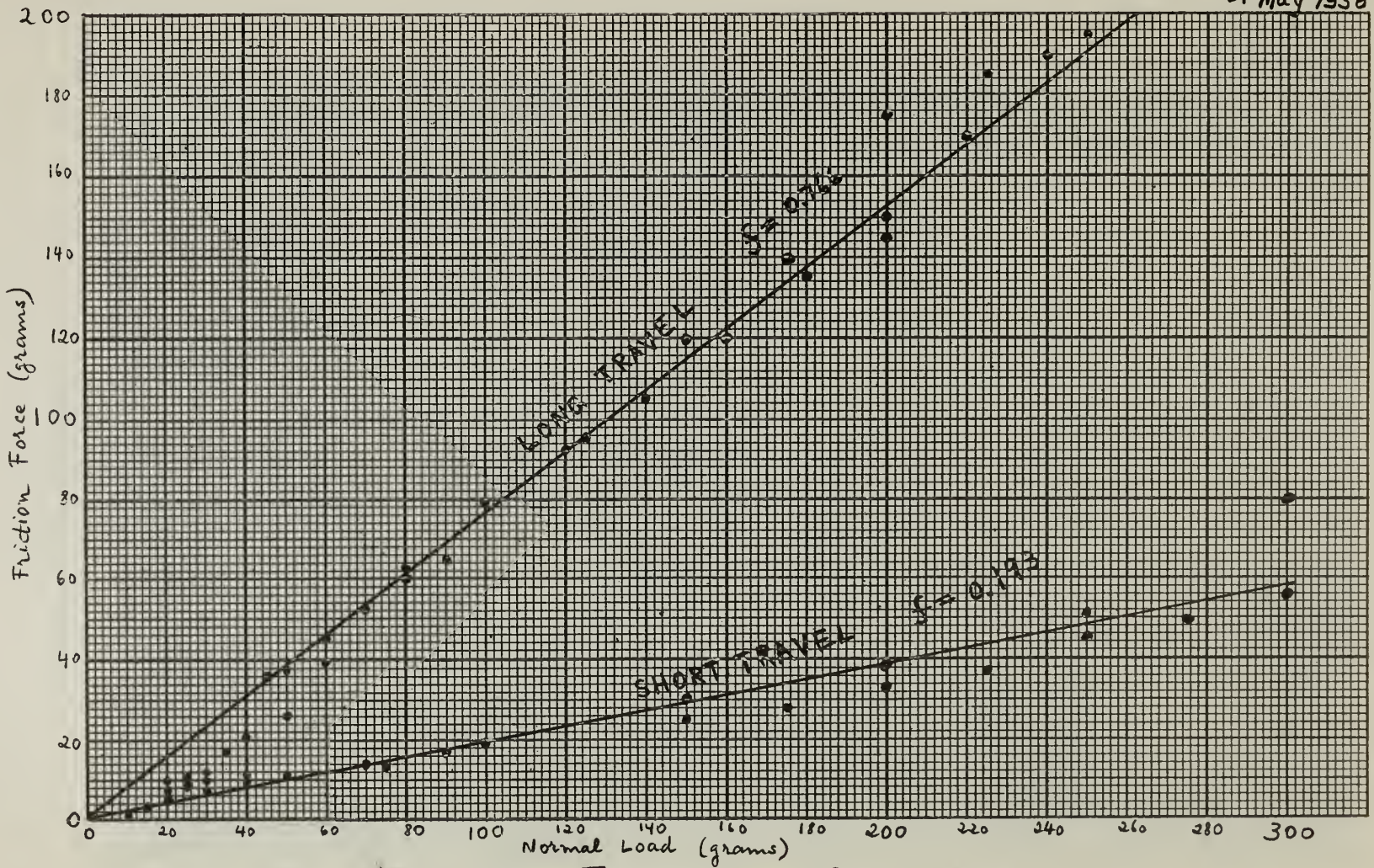

FIGURE VIII.- FRICTION FORCES ON SPECIMEN B

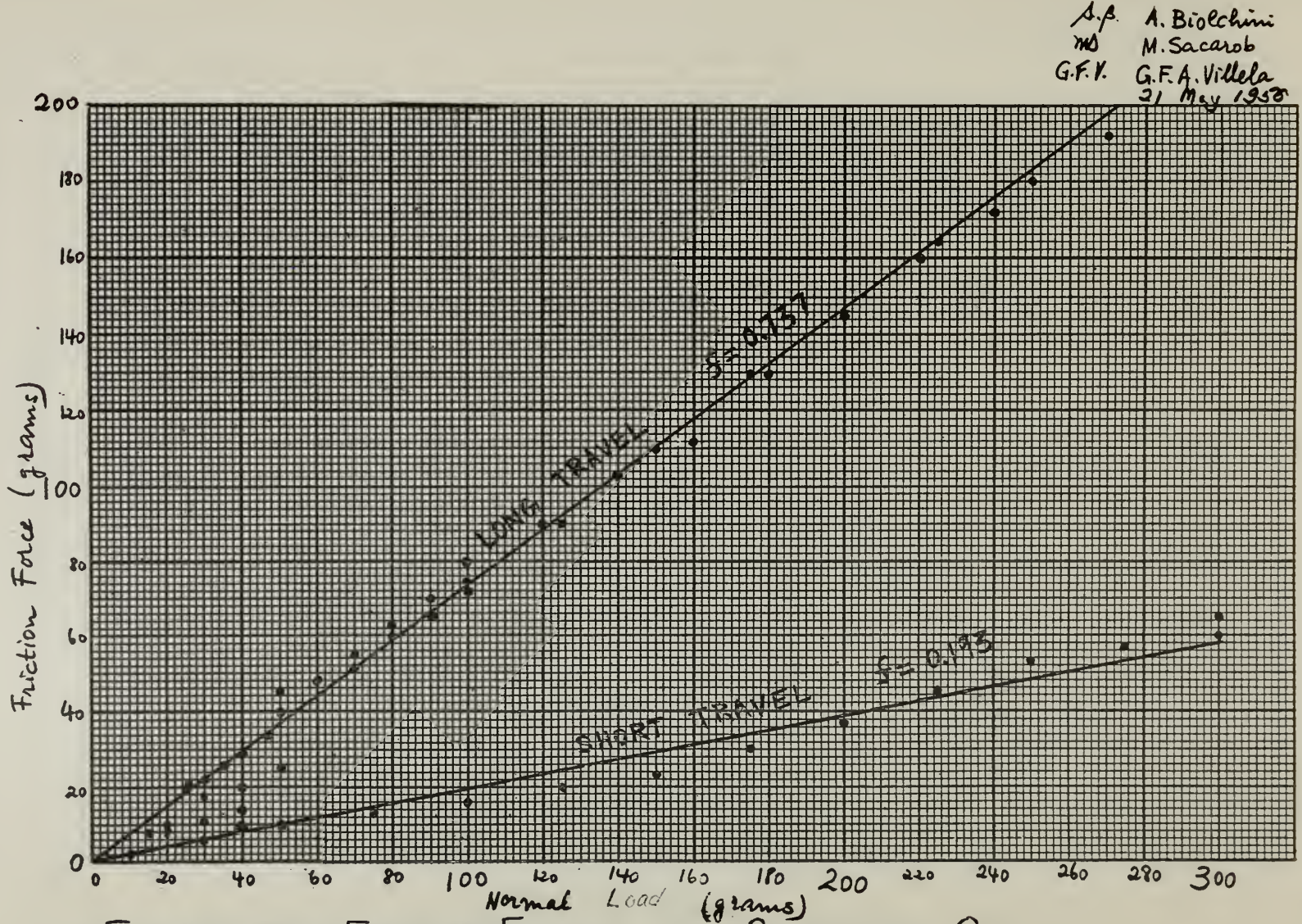

FIGURE IX.- FRICTION FORCES ON SPECIMEN C

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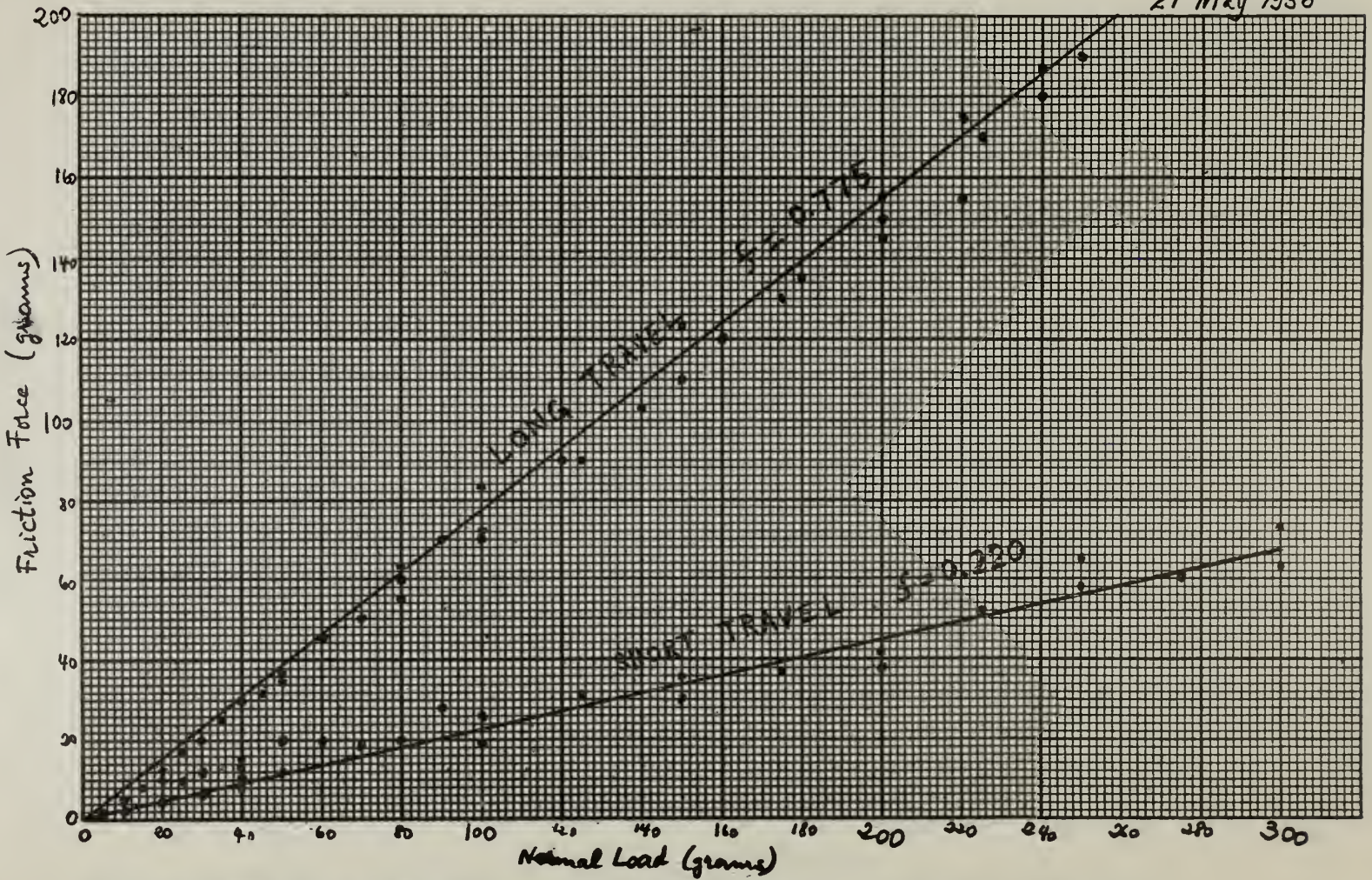
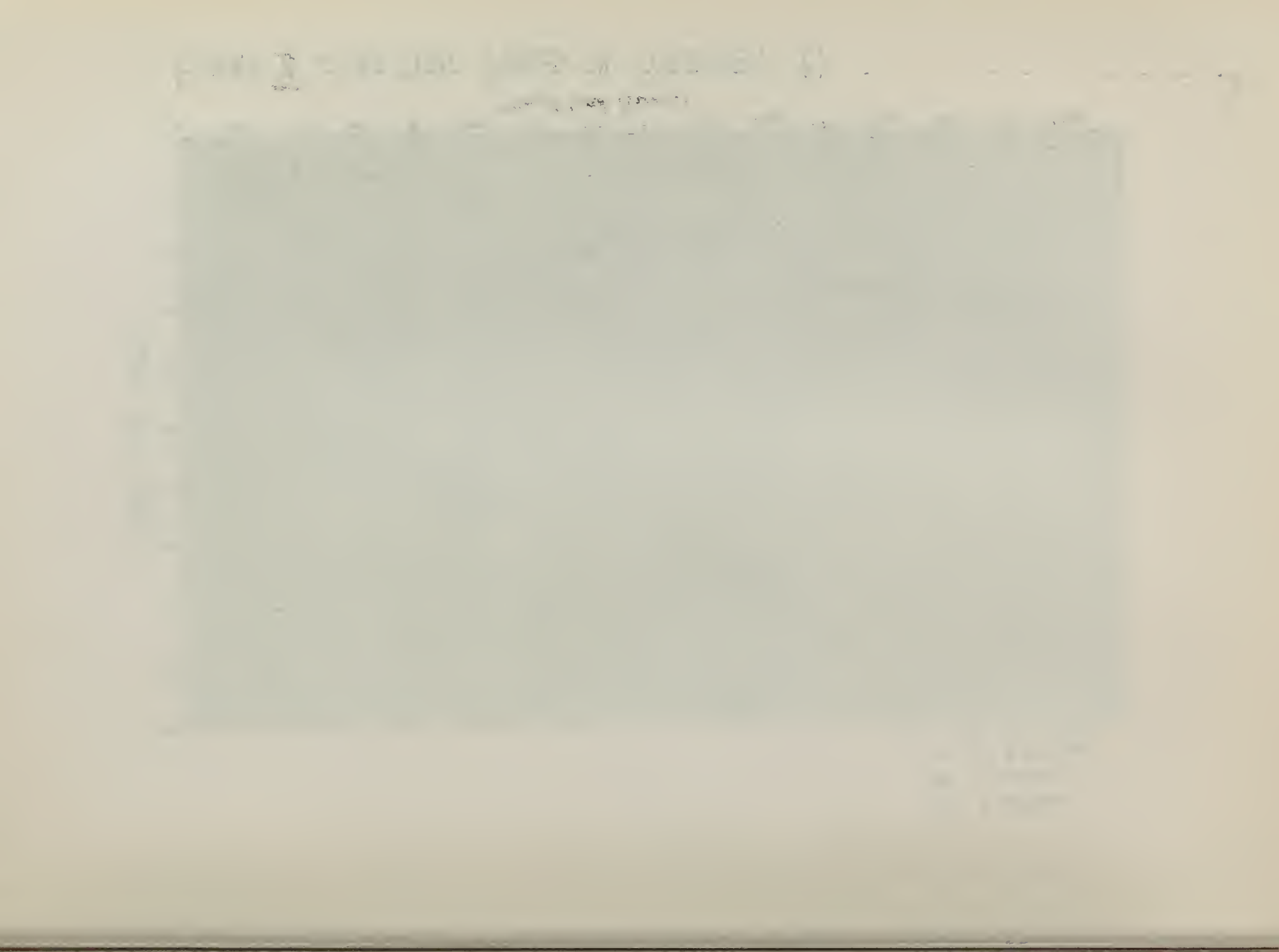


FIGURE X - FRICTION FORCES ON SPECIMEN D



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G.F.V. G. F. A. Villela
21 May 1956

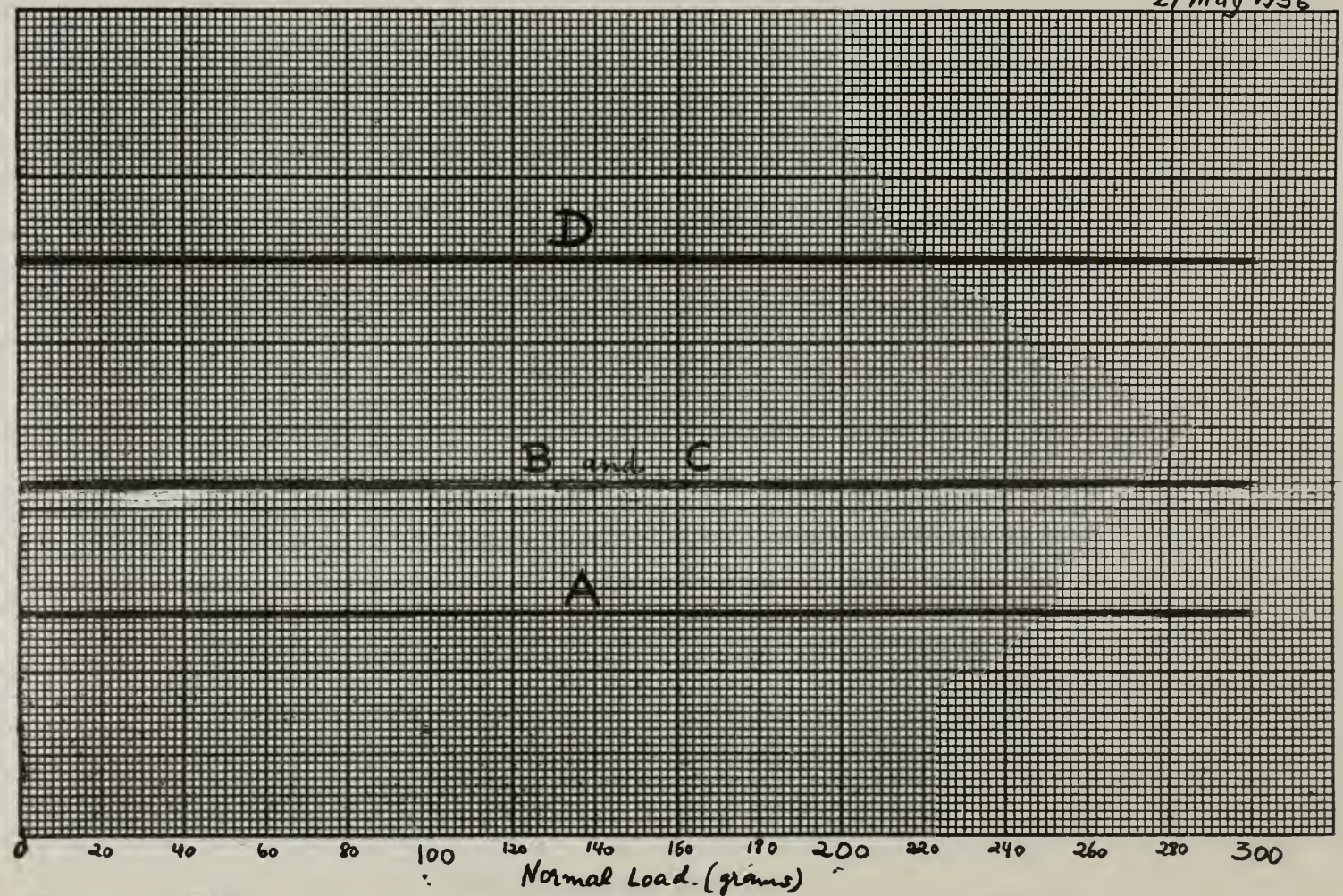

FIGURE XI.- FRICTION COEFFICIENTS - SHORT TRAVEL

A.B. A. Bioldini
M.S. M. Sacarob
G.F.V. G.F.A. Villela
21 May 1956

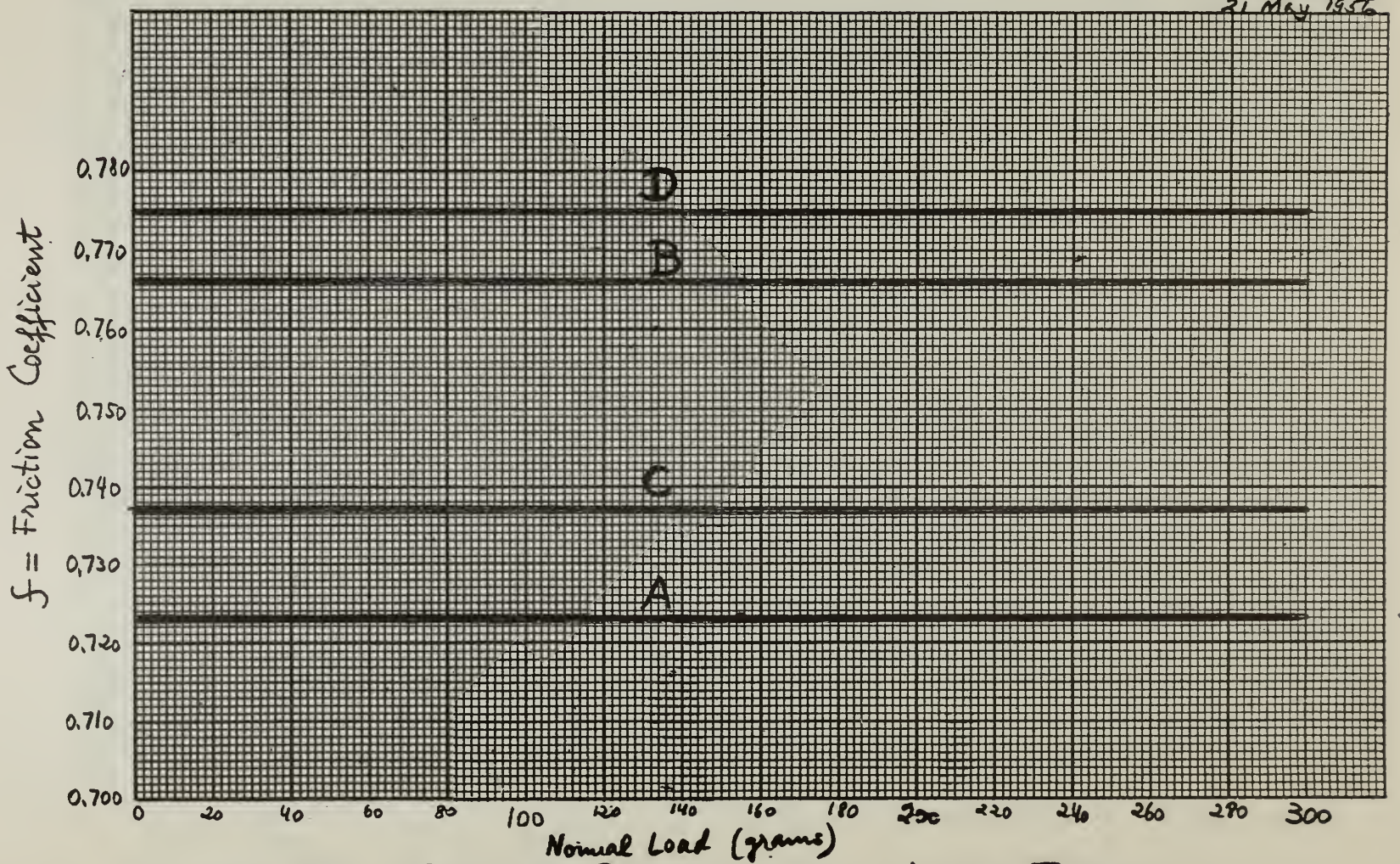

FIGURE XII.—FRICTION COEFFICIENTS- LONG TRAVEL

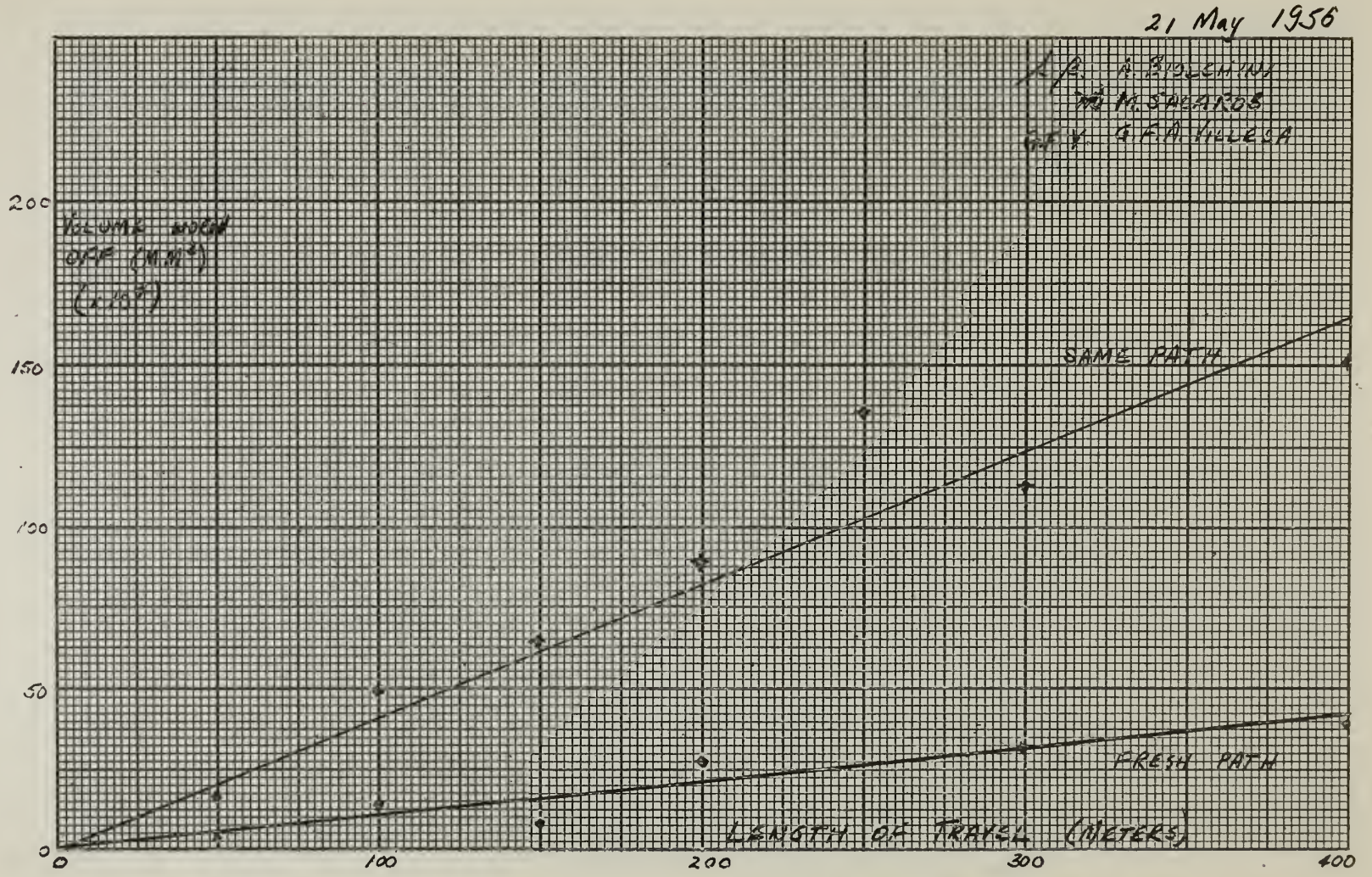

FIGURE XIII. VOLUME WEAR ON SPECIMEN A WITH 300 GRAMS NORMAL LOAD

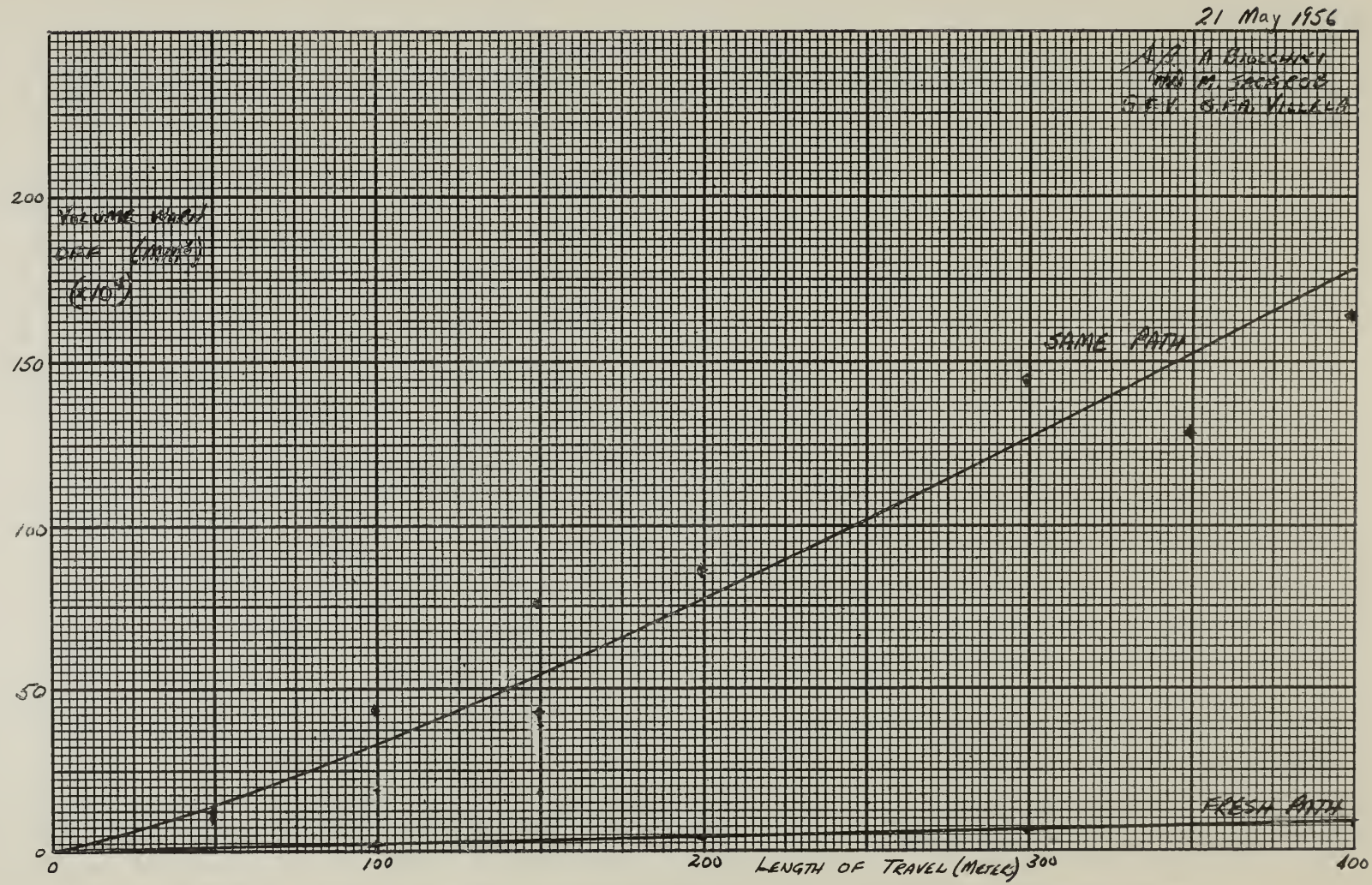

FIGURE XIV. VOLUME WEAR ON SPECIMEN B WITH 300 GRAMS NORMAL LOAD

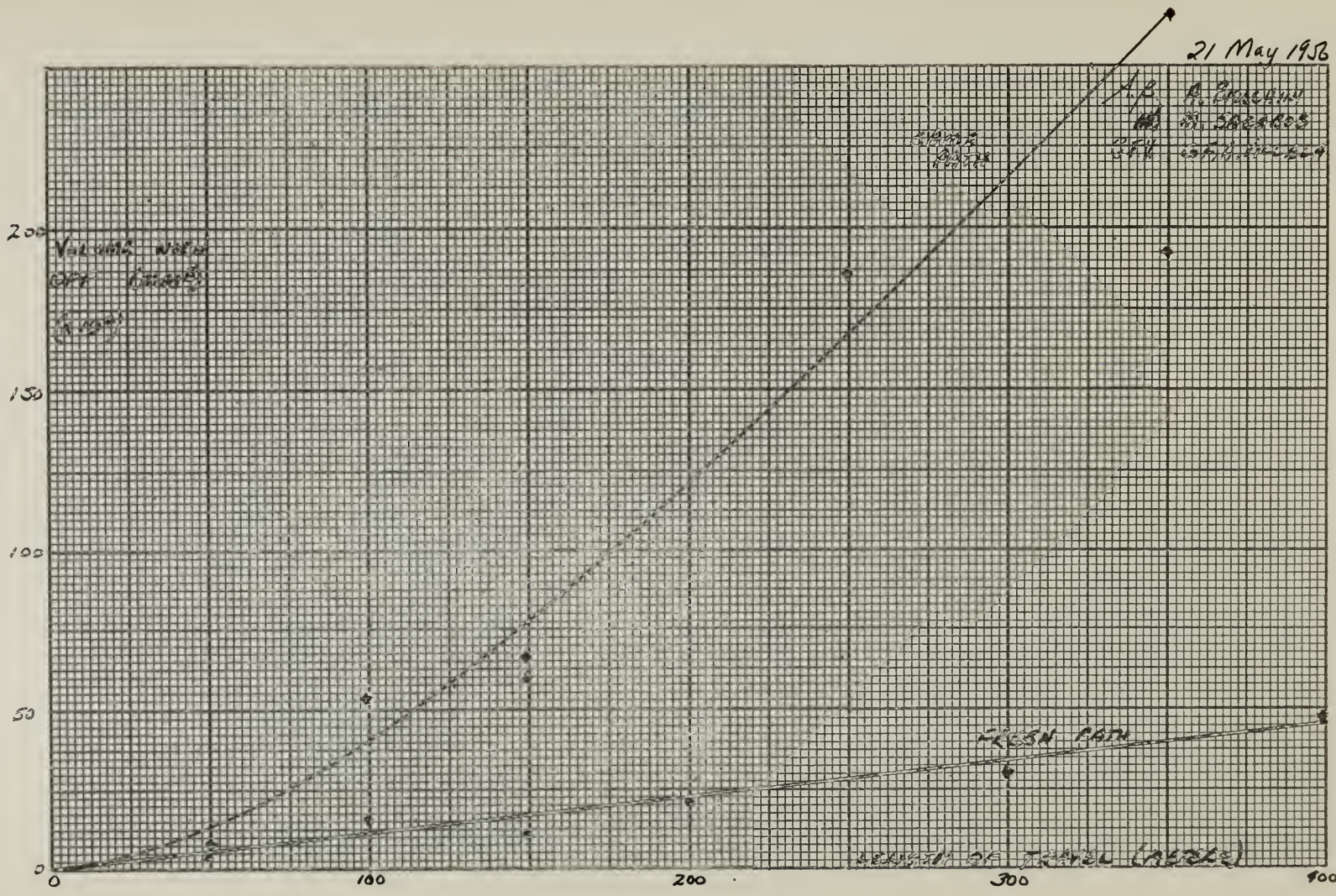

FIGURE XV. VOLUME WEAR ON SPECIMEN C WITH 300 GRAMS NORMAL LOAD

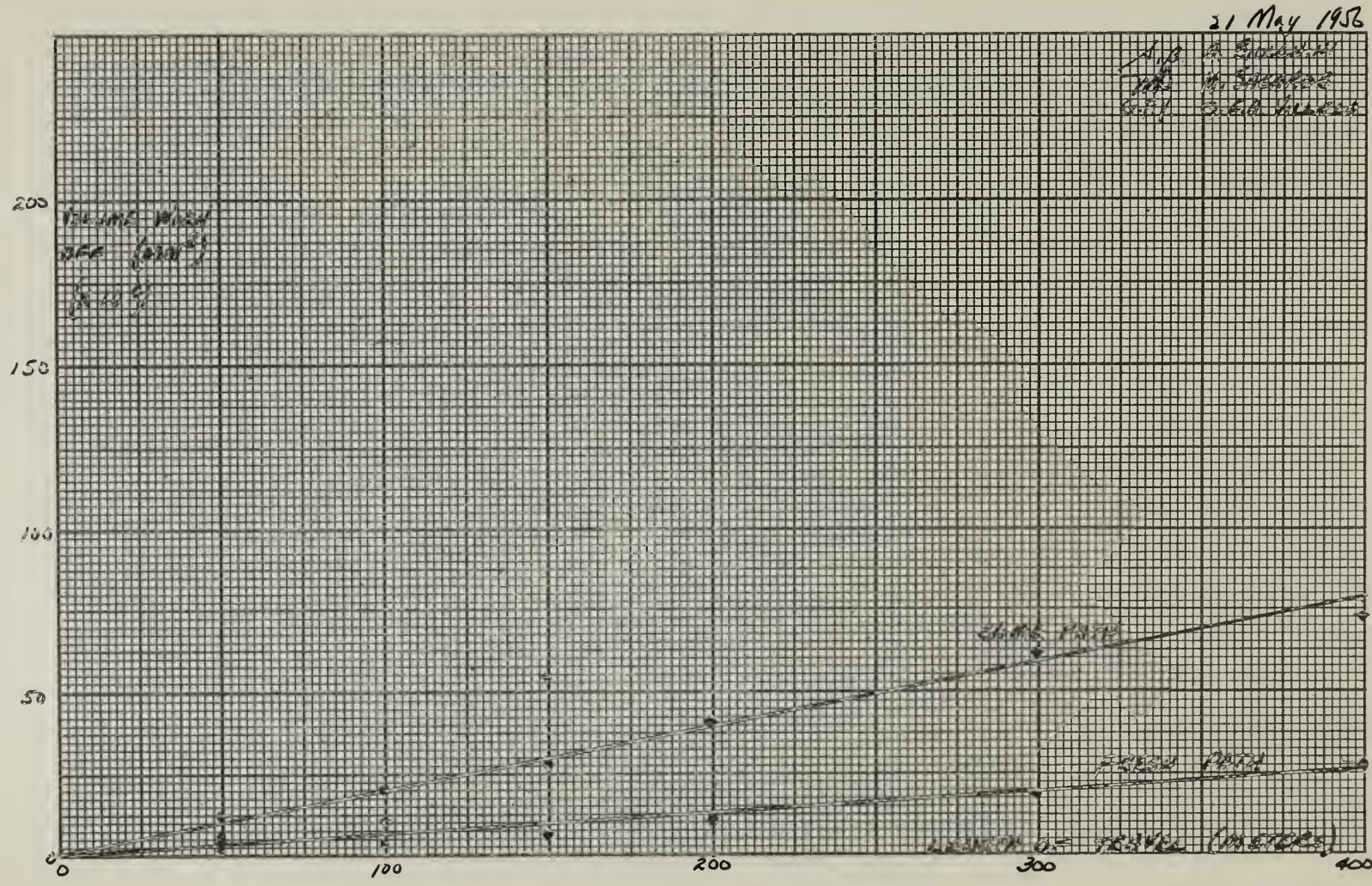

FIGURE XVI. VOLUME WEAR ON SPECIMEN D WITH 300 GRAMS NORMAL LOAD

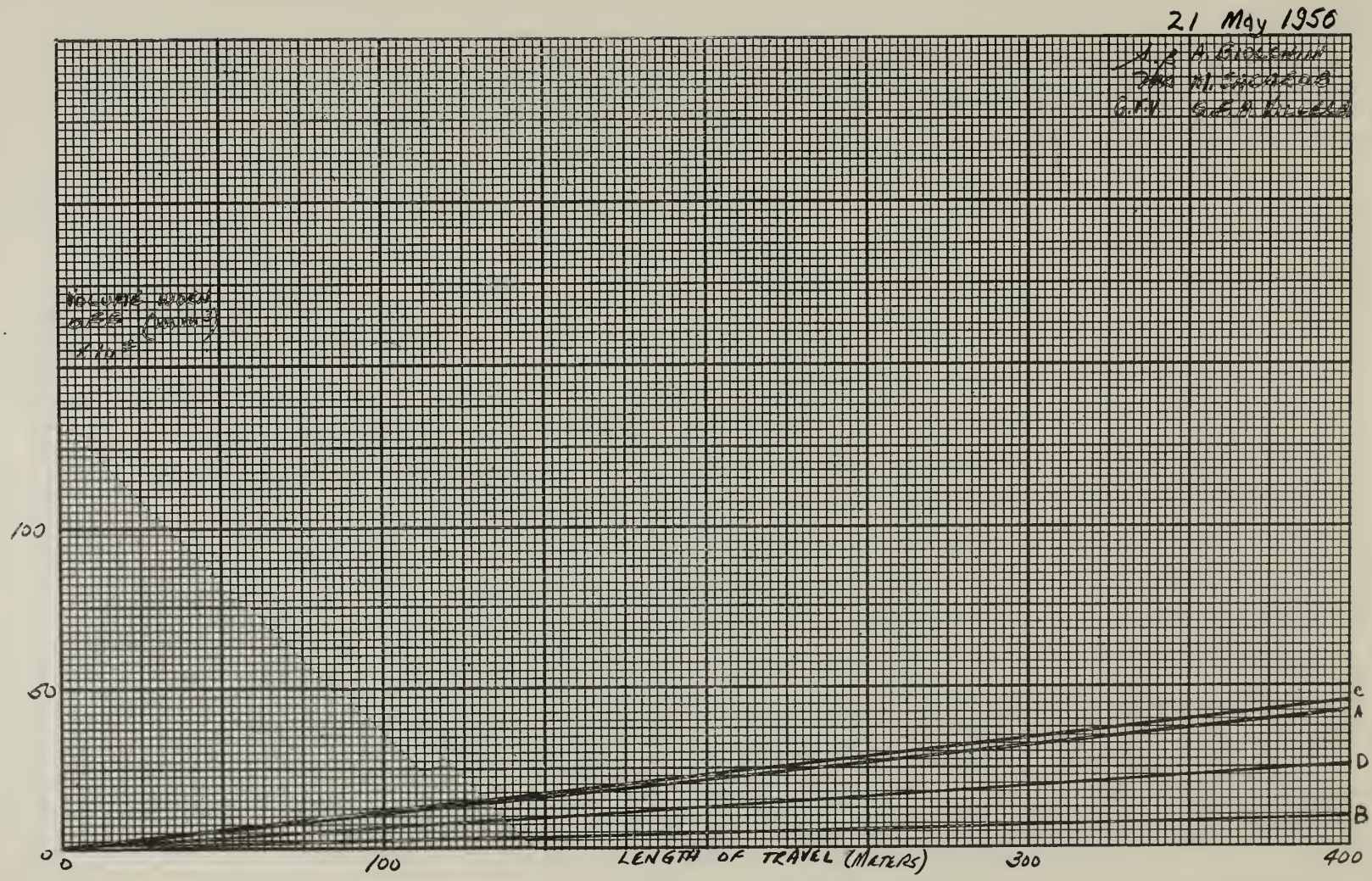

FIGURE XVII. COMPARATIVE WEAR ON SPECIMENS A, B, C, & D, FRESH PATH, 300 GR. LOAD

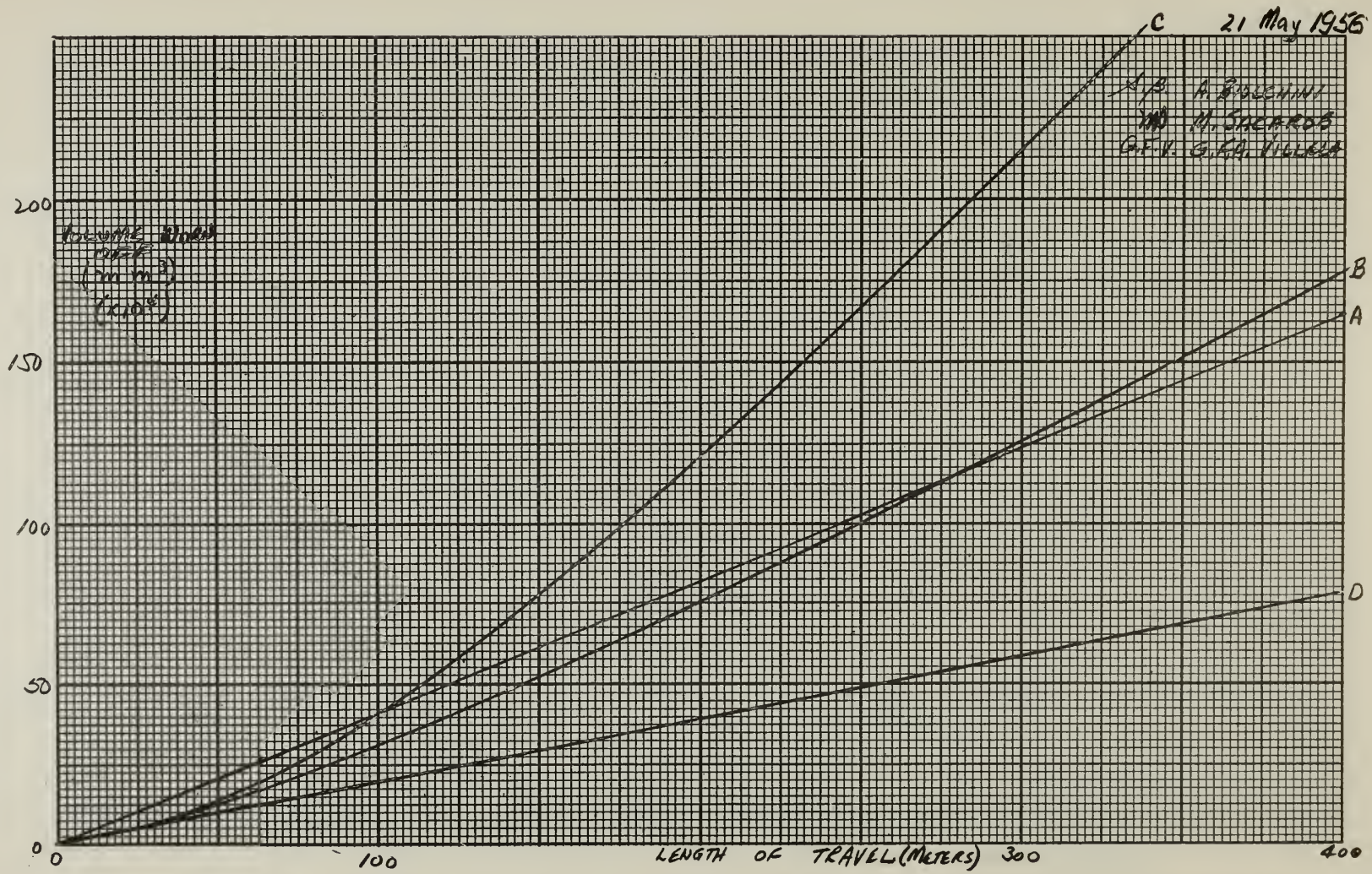

FIGURE XVIII COMPARATIVE WEAR ON SPECIMENS A, B, C, & D, SAME PATH, 300 GR LOAD

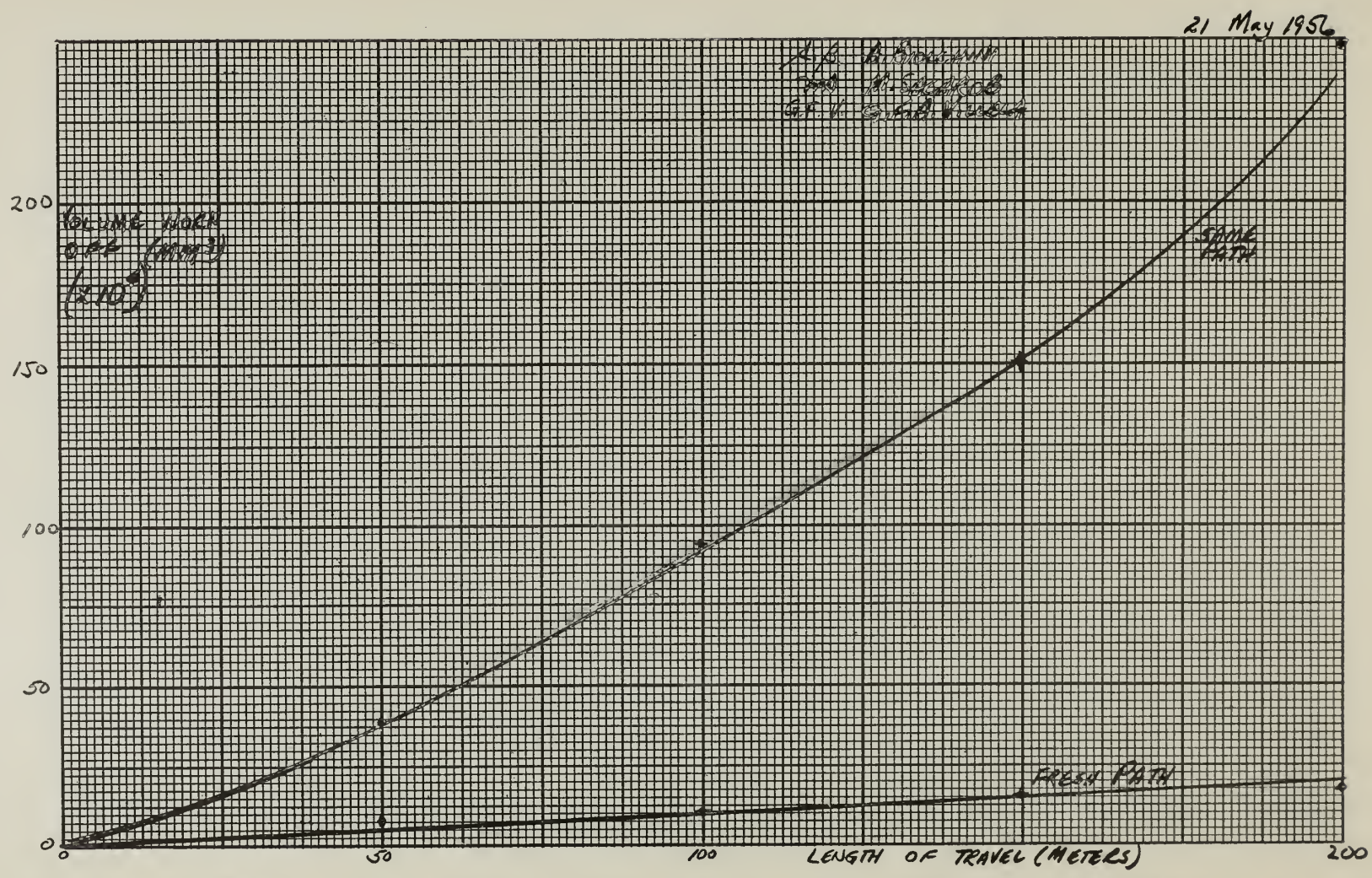

FIGURE XIX. VOLUME WEAR ON SPECIMEN A WITH 600 GRAMS NORMAL LOAD

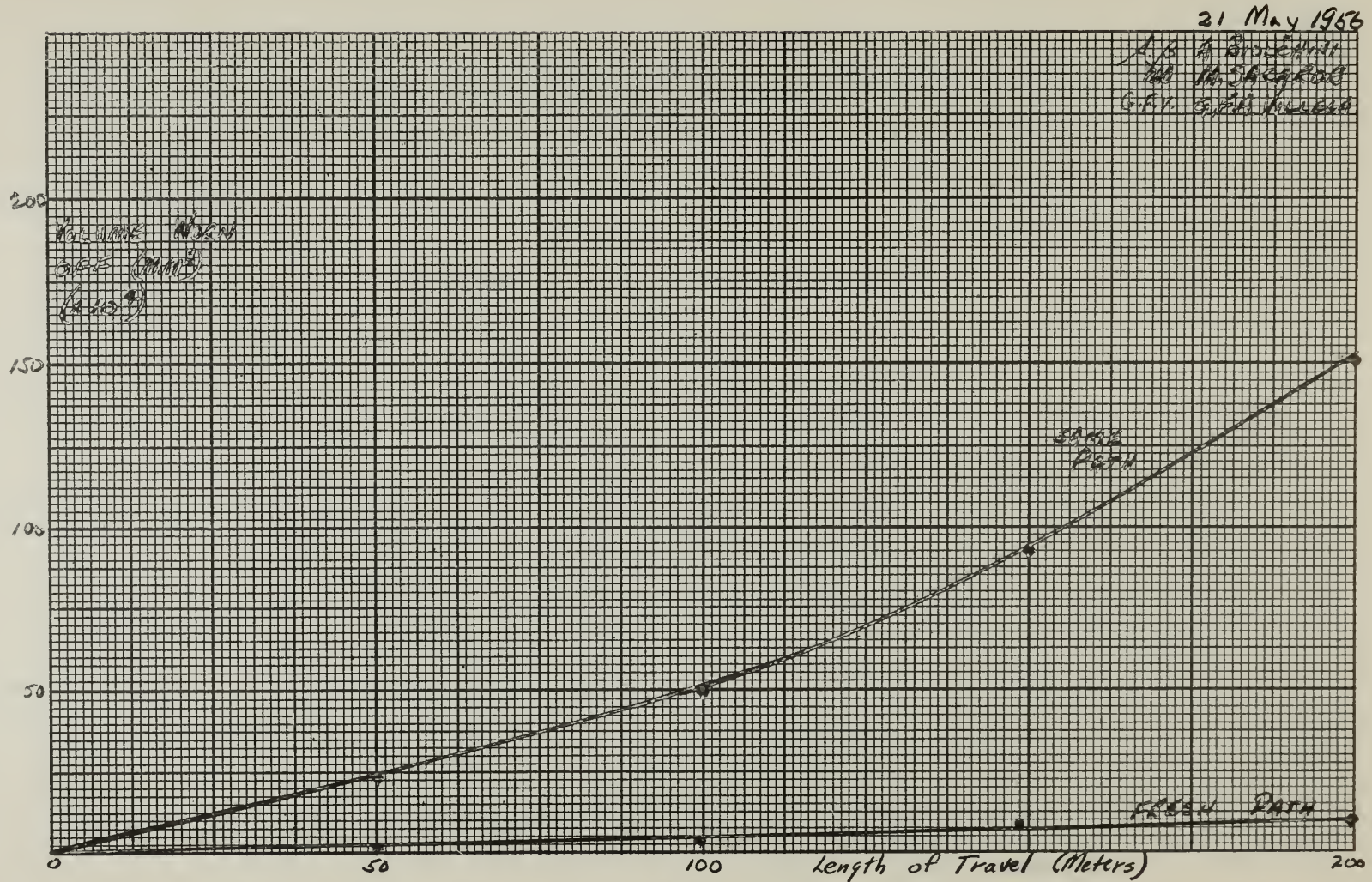

FIGURE XX. VOLUME WEAR ON SPECIMEN B WITH 600 GRAMS NORMAL LOAD

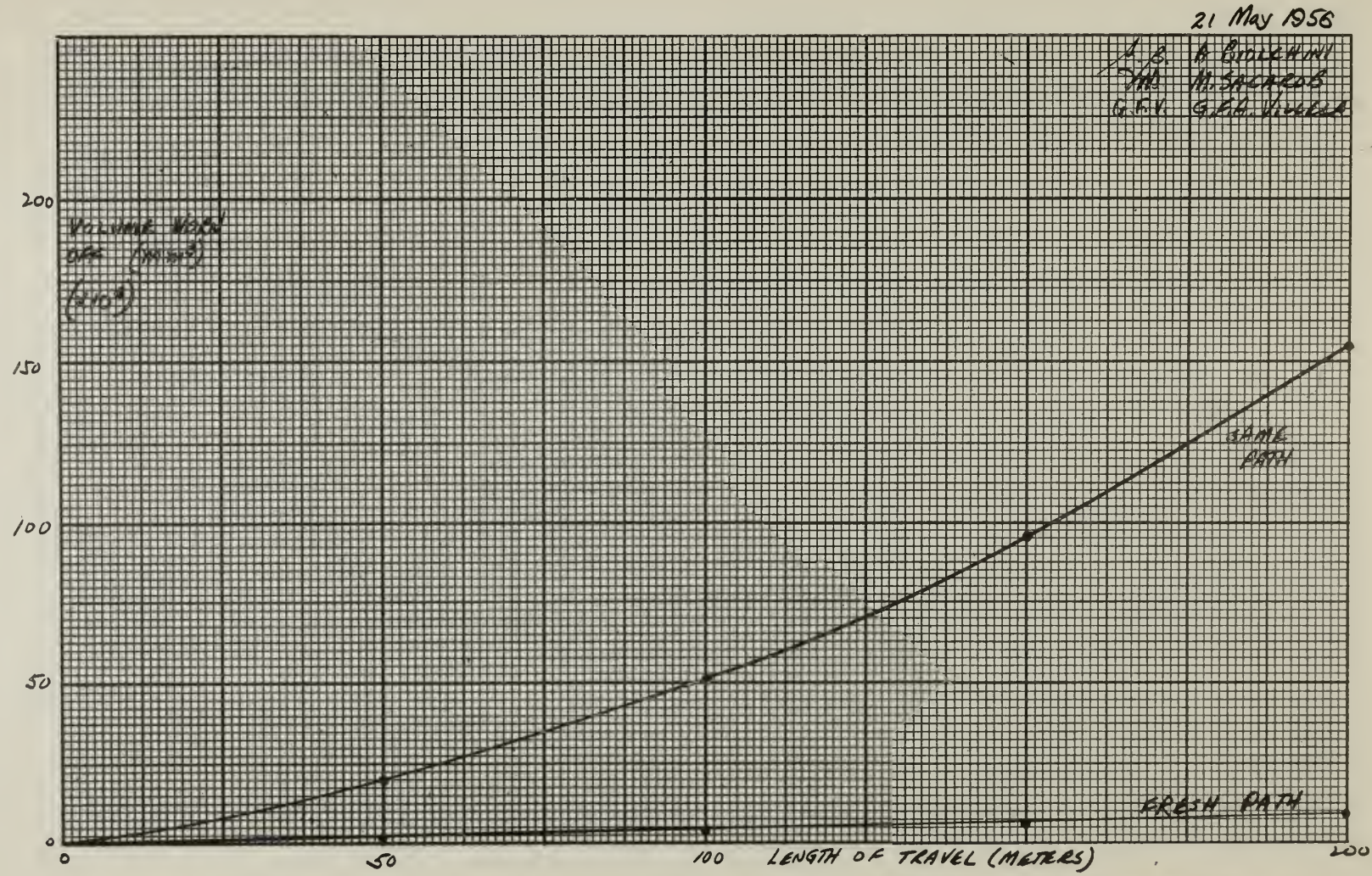

FIGURE XXI. VOLUME WEAR ON SPECIMEN C WITH 600 GRAMS NORMAL LOAD

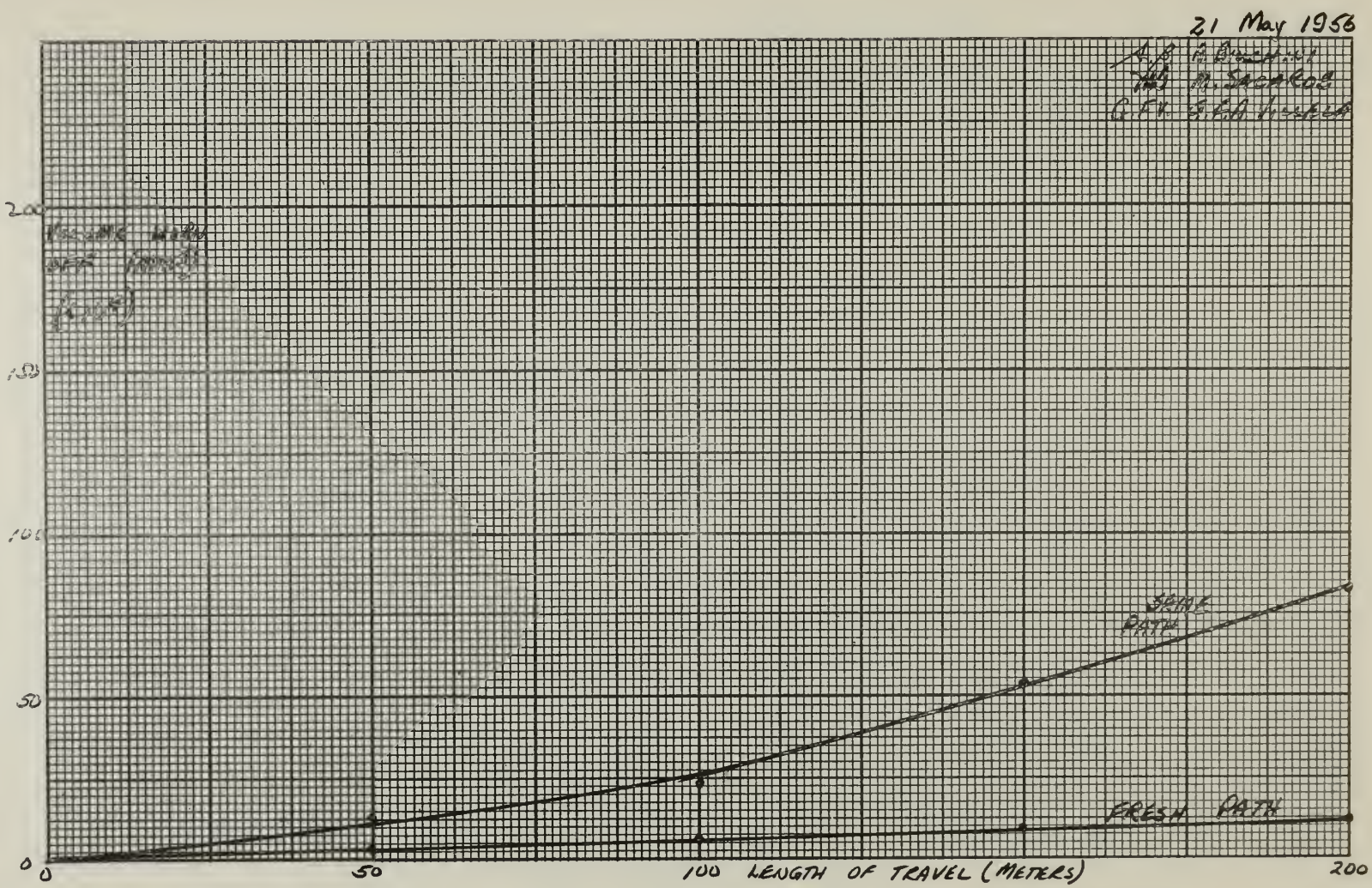

FIGURE XXII. VOLUME WEAR ON SPECIMEN D WITH 600 GRAMS NORMAL LOAD

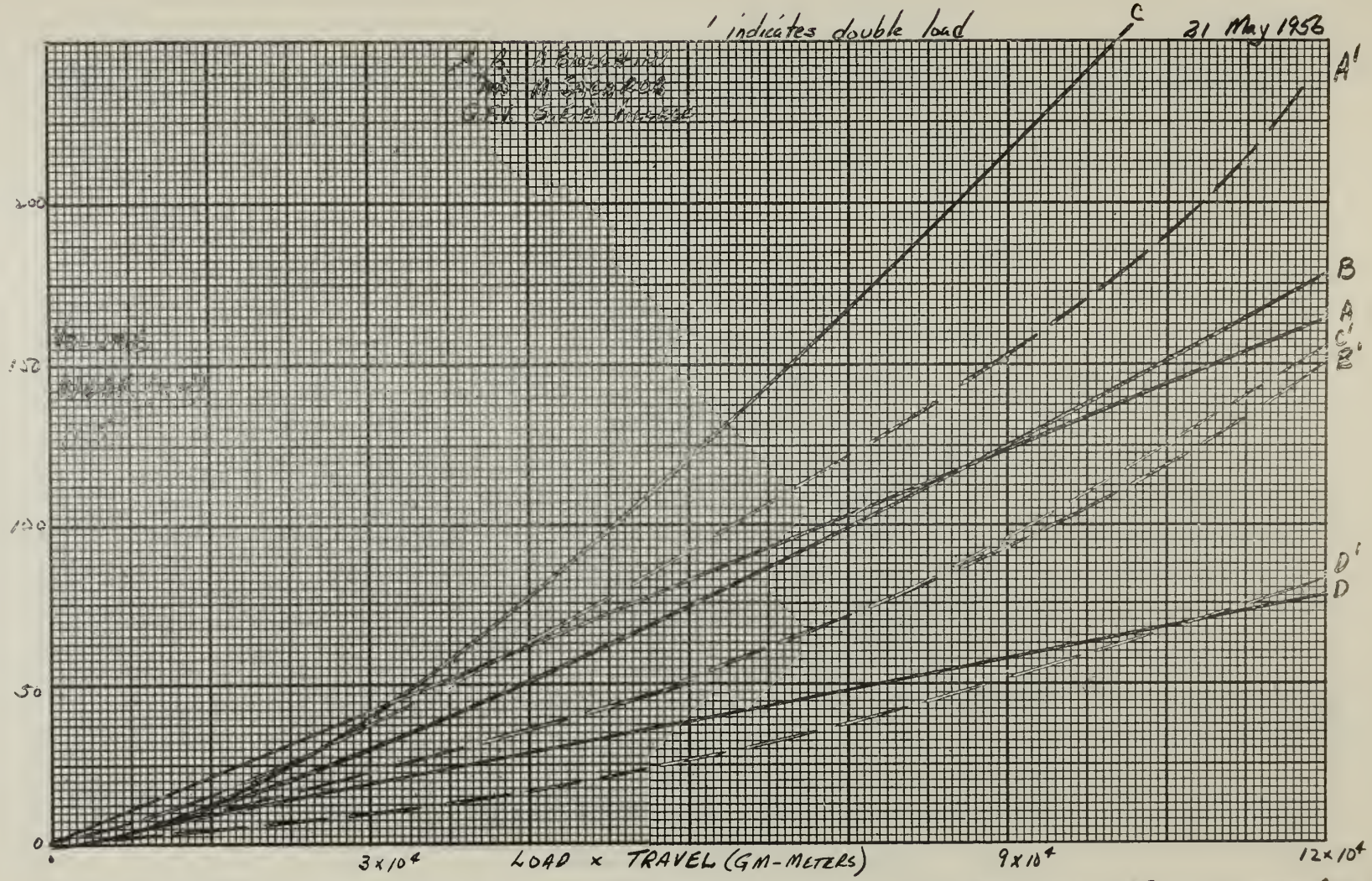

FIGURE XXIII. COMPARISON OF ALL TESTS ON BASIS OF LOAD TIMES TRAVEL, SAME PATH

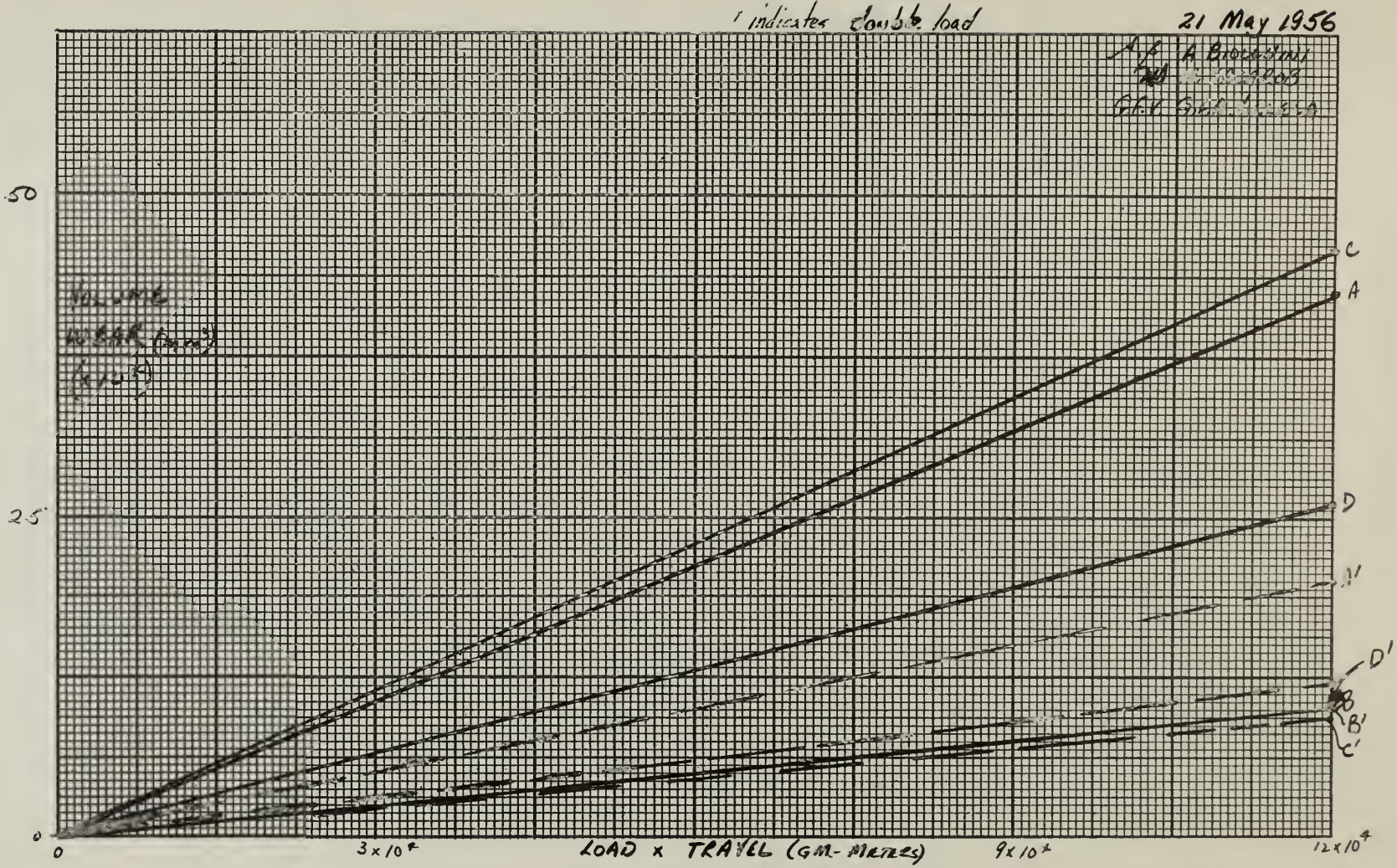

FIGURE XXIV. COMPARISON OF ALL TESTS ON BASIS OF LOAD TIMES TRAVEL, FRESH PATH

DISCUSSION OF RESULTS

A) Friction

The results of the friction experiments have been plotted as points on Figures VII through X; it has been verified that straight lines could be drawn through these points, representing the mean values of the friction force in each case. On Figures XI and XII the friction coefficients are plotted for better comparison between the specimens. As suggested in the Introduction, the friction forces for each type of specimen should have both a minimum and a maximum value across the whole range of normal loads used, depending on whether a short distance or a longer one is traversed over the same path, due to the instability of the martensite in the disk. This has been observed experimentally.

The curves which indicate lower friction coefficients were obtained with travels up to about 0.8 meters, or twice over the same path, and are attributed to a martensitic disk. The curves with greater slope are the results of runs beyond approximately 10 meters, or twenty five passes over the same path, and may be explained by the degeneration of the martensite in the disk due to the pressures and temperatures developed at the interface.

It was also observed that values between these two extremes could be obtained if the distance traveled fell between 0.8 and 10 meters. For any specified value of the

normal load, if the specimen is allowed to run indefinitely over the same path on the disk surface and at the same time a record of the friction force is made, it is observed that the friction coefficient in the beginning is given by the corresponding curve on Figure XI. However, after some time, the friction coefficient begins to rise with time and tends, in the limit, to the value of the corresponding curve on Figure XII.

The influence of hardness and heat treatment on the friction coefficient is small. For the same hardness level, the friction coefficient is higher with a higher hardening temperature. On the other hand, for the same hardening temperature the friction coefficient increases with increasing hardness. These results are consistent for both short and long lengths of run. This behavior is predicted by Bowden and Tabor (reference 2) which states that the relative properties of the sliding metals are the important parameters of the phenomenon.

Whether the disk is highly martensitic or not, it has been verified that its hardness always exceeds that of the sliders. Therefore, the higher the hardness of the slider, the more similar it is to the disk in this respect, and a greater friction coefficient is expected.

As to the influence of the hardening temperature, it is more difficult to correlate. An interpretation could be attempted by extending the Bowden and Tabor theory to the metallographic microstructure of the metals. The higher

the hardening temperature of the specimens the more similar would be their microstructure to the microstructure of the disk, with a consequently higher friction coefficient. However, further experiments would be necessary to verify this.

The fact that the experiments were conducted under normal atmospheric conditions did not bring inconsistency of results as might have been expected.

B) Wear

An examination of Figure XVII indicates that there is a definite difference in the wear of steel samples. We find that the plots on this graph show two groupings - a grouping together of the lines A and C, and another of the lines B and D. An examination of the table on page 14 shows that this must be a natural division, because A and C were subjected to the same original hardening temperature, which would govern the structure, although later annealed to attain the desired hardness. So it is also with B and D.

We can also see that there is a smaller difference between the lines A and C, and between B and D. We find that the lines representing the harder slider fall above the corresponding line of the softer slider.

Therefore we can say that if there is only adhesive wear present, the steel that is brought to the lower hardening temperature will generally wear to a greater degree

than that brought to the higher temperature, and of two steels brought to the same hardening temperature, the softer of the two will wear to a lesser degree than the harder.

The picture is less clear as we examine Figure XVIII. There are no definite conclusions to be drawn from this with respect to corrosive wear. It is believed that the interaction of the wear processes involved affected the results of this part of the experiment.

In examining Figures XIII through XVI, we find that in all cases, as expected, the wear found on the same path runs exceeded that found on the fresh path runs. This bore out Burwell's theory, since, when running on the same path, we have corrosive wear in addition to the adhesive wear that is found in all sliding friction.

In all runs where there was adhesive wear only, the wear appears to be a linear function of distance traversed. This is not the case when the slider moves over the same path. The slight curvature of the plots indicates that the volume wear increases with a power of L slightly greater than one. This may be explained by the effect of the oxide powder left on the track. The amount of this oxide increases with the wear, and it also increases the rate of wear. It may be that these two features combine to cause the phenomenon observed.

In Figures XIX through XXII are plotted the results of runs made with double the load, and over half of the

distance. These plots verify the linearity of the adhesive wear with travel. Burwell's theory says that volume of wear is proportional to normal load multiplied by the distance of travel. Therefore, a slider with three hundred grams normal load should have lost as much material after four hundred meters travel as a slider with six hundred grams after two hundred meters travel.

In Figure XXIII and XXIV all of the curves obtained are plotted on a load times distance base. In the fresh path runs, involving adhesive wear only, the wear on the slider with the greater load is in every case less than the wear on the slider with the lighter load. This indicates that the power of the exponent of load should be less than unity. Again, unfortunately, a comparison of the curves obtained from using the same path do not indicate anything conclusive. It is assumed that the interaction effects mentioned previously account for this.

Since we have seen previously that wear varies with a power of distance greater than unity, and now that it varies with a power of load less than unity, we should expect a smaller difference between the actual data and that based on the proportionality, depending on the strength of each factor. By examining Figure XXIII we can find no correlation between hardness and heat treatment and an effect upon the proportionality of wear to length of travel times load.

The fact that the wear increased with hardness and

decreased with hardening temperature was predicted by Bowden and Tabor, as explained in the Introduction. The variation of friction was also predicted and explained in the Introduction.

Both friction and wear increase with hardness, and this is explained by the fact that the hardness of the sliders approach that of the path, particularly after the martensite on the path has degenerated a bit. Thus the two metals approach each other in hardness and act more like similar materials.

The correlation between friction and wear appears to be extremely tenuous. It cannot be said that higher friction exists with greater wear. This must be qualified. It appears in this set of experiments that for a given heat treatment, the material with the greater friction coefficient also is subject to the greater wear. This leads us to believe that for a given material, if we choose the softer of the metals, we enjoy the double advantage of less wear and less friction, although this advantage is admittedly small. If we accept a single hardness then we find that the friction coefficient is higher for the metal subjected to a higher hardening temperature but the wear is less. Thus we see that any correlation between friction and wear must depend on the parameters that we have explored and cannot be drawn without reference to these parameters.

VI. CONCLUSIONS

The following conclusions were arrived at:

1. The coefficient of friction will increase in all cases as the slider continues to retrace the same path.

2. The influence of hardness and heat treatment on the friction coefficient is small. The friction coefficient increases with hardness and with increasing hardening temperature.

3. With only adhesive wear present, wear decreases with decreasing hardening temperature and with increasing hardness, with the former exerting a greater influence.

4. Burwell's theory that wear is proportional to the product of load and distance traversed was not borne out. It appears as though exponents must be required, with the exponent of load being less than unity and that of distance travelled being greater than unity.

5. There appears to be some correlation between friction and wear, but this seems to be small. It appears that wear will decrease as friction increases, for the same hardness, and will increase as friction increases for the same hardening temperature.

VII. RECOMMENDATIONS

It is suggested that the experiments of both friction and wear, over a fresh path and over the same path, be conducted in an inert atmosphere. If different wear and friction are registered between fresh path and same path runs, it should be attributed to the change of one surface due both to picking up material from the other surface and to the decay of the martensite. In the limit the wear should be characteristic of sliding of equal materials. The corrosive wear will be absent.

Now, based on this data, an estimate of the influence of transferred material on wear should be made and deducted from our data in order to obtain a more accurate estimate of the corrosive wear.

The interactions that exist will make a friction correlation more difficult than in the wear case. However it is believed that some conclusions could be drawn from these further tests as far as friction coefficients are concerned.

It is also recommended that further experimentation be done to check effectively the variation of wear with load and length of travel. Only one set of tests were made in this thesis with this in mind, and it is not considered that these tests were conclusive.

APPENDIX

APPENDIX A

Burwell's theory, which is discussed briefly in the Introduction to this thesis, should be more fully explained. As explained previously, Burwell classifies wear into five categories. In his first category, adhesive or galling wear, we have said that it is caused by the welding of small points of contact and the subsequent tearing of these welds. Regardless of how smoothly and finely finished they are, two surfaces brought into contact will touch at only a relatively few isolated points. These points carry all of the load that is put on the two surfaces. Consequently the pressures at those points of actual contact are extremely high and usually exceed the yield point of the softer of the two materials in contact. As a result of these high level pressures combined with the relative slide motion, minute welds are formed at each of the local contact areas.

With continued sliding these welds are sheared. While they often shear on the original surface of contact because the weld for some reason does not have full strength, still a certain fraction of the welds formed will be as strong or stronger due to work-hardening, than the softer of the two base materials with the result that these welds shear not at the initial surface of contact but to one side, generally towards the softer of the two metals. The net result is that some of the softer material has become transferred to the other, harder surface. This may

remain adhering to the latter surface and ultimately be worked into it, or else subsequent sliding may knock it loose, resulting in a loose wear particle.

The amount of adhesive wear can be profoundly affected by the nature of the surfaces and the ambient conditions. The same or similar materials show greater transfer than very dissimilar ones. A very clean surface greatly facilitates adhesive wear. High temperature increases and accelerates adhesive wear, and materials with low melting points gall much more than do materials with high melting points operating at the same temperature. In many instances the temperature in question may be generated by the frictional heat of rubbing. By using the low speed of 30.6 centimeters per second, this effect was avoided.

Burwell presents this expression for adhesive wear alone:

$$V = k\, W \cdot L/H = k'\, W\, L \qquad (1)$$

where

V represents the volume of material removed

k and k' are wear constants

W represents the normal load pressing the two surfaces together

L represents the length of travel

and H represents the indentation hardness of the softer of the two surfaces.

Burwell checked the validity of his theory by ex-

perimental results, through the constant k'. He varied W and L separately, and he obtained straight lines in both cases, indicating that he was correct. In our experiments, we will incidentally check this formulation by varying H and L, to see whether k will be constant or not.

Burwell's objective was to define a constant k', which is a characteristic of the material, at least for a range of moderate loading, called "the adhesive wear coefficient" and which could be measured for various pairs of materials and could be used by the engineer in much the same way that he uses friction coefficients. Burwell discovered that for high loads, those generally exceeding the range of accepted engineering practice, the adhesive wear coefficient k' was no longer constant but increased rapidly with the load.

Abrasive wear was briefly described also. There are two situations in which this can happen; one, where the hard surface in question is the harder of the two rubbing surfaces, and two, where the hard surface is a third body, generally a small particle of grit or abrasive, caught between the two surfaces and sufficiently harder than either, so that either one or both of the surfaces are abraded. The first is referred to as cutting wear and the second as abrasive wear.

The primary requirement for cutting wear is that there be a great dissimilarity in hardness between the two rubbing surfaces and in addition that the harder of the two

possess a certain definite amount of roughness. In abrasive wear the small particle may come from the air or from the products of corrosive wear, generally metal oxides which are sometimes harder than the parent metal. Iron oxide, Fe_2O_3, also used for jeweler's rouge, is one of these products. Hence these particles produced initially by corrosive wear, if they remain between the surfaces, will then cause abrasive wear.

In an attempt to formulate corrosive wear, Burwell arrived at the following expression:

$$V = \frac{WrC}{H} \ln\left(\frac{l}{f\gamma} + 1\right) \quad \frac{L}{l} = k'' W L \ln\left(\frac{l}{f\gamma} + 1\right) \qquad (2)$$

where V, W, H, and L have the same significance as before,

r represents a factor indicating the average fraction of the total oxide film removed,

C and γ are empirical constants characteristic of the system, describing the corrosion rate of the surfaces in a given environment. They are defined by the "logarithmic law": h = film thickness = $C \ln\left(\frac{t}{\gamma} + 1\right)$, where t is time.

f represents the frequency of revolution,

l represents the length of the track per cycle (equivalent to the circumference of the cylinder).

Comparing this equation with equation (1), it can be seen that the dependence on the load and the length of travel is the same. However, the amount of corrosive wear depends also on the frequency of rotation or reciprocation

over the same area. Equation (2) was not checked experimentally by Burwell.

An attempt to verify equation (2) may be unsuccessful due to the interaction of corrosive wear and adhesive wear, which would cause the amount of wear to be greater than expected. This interaction is called "fretting corrosion", and it commonly occurs in situations where slight vibratory motion exists. For steel it is characterized by a voluminous amount of reddish brown oxide. Also there is the interaction between the corrosive wear and abrasive wear; this was mentioned previously.

B. SAMPLE CALCULATIONS

For calculating the volume of material worn from the slider, it was assumed that the wear spot was a plane surface. Where the wear spot appeared as an ellipse, a small amount of accuracy was sacrificed, and it was assumed to be a circle of mean diameter. In this way the volume of the worn material could be calculated as the volume of a segment of a sphere. The formula for this is

$$\text{Volume} = \pi h^2(3R - h)/3$$

where h is the height of the segment measured along the radius of the sphere which is perpendicular to the plane of the wear spot and R is the radius of the sphere. Solving for h as a function of R and a, the radius of the wear spot, both of which can be measured:

$$h = R - \sqrt{R^2 - a^2} \qquad \text{and}$$

$$V = \frac{\pi}{3}\left(2R^2 - a^2 - 2R\sqrt{R^2 - a^2}\right)\left(2R + \sqrt{R^2 - a^2}\right)$$

Reading on microscope of spot diameter - 46.5 marks

Microscope constant - .0247 mm per mark

a = (Reading)(Constant) ÷ 2 = 0.574275 mm; R = 3.4544 mm

$a^2 = 0.329791776$ $\qquad$ $R^2 = 11.93287936$

$\sqrt{R^2 - a^2} = 3.406330516$

$2R^2 - a^2 - 2R\sqrt{R^2 - a^2} = 0.002310675$

$2R + \sqrt{R^2 - a^2} = 10.315130516$

Volume worn off = 0.02495984

Calculations were made to eight decimal places but accuracy did not require this, so the figures were finally rounded off somewhat. Some accuracy was lost in reading the microscope, which could only be read to one half of a division with surety. Furthermore, this accuracy could be taken advantage of only on an extremely large graph, too large to include in this thesis.

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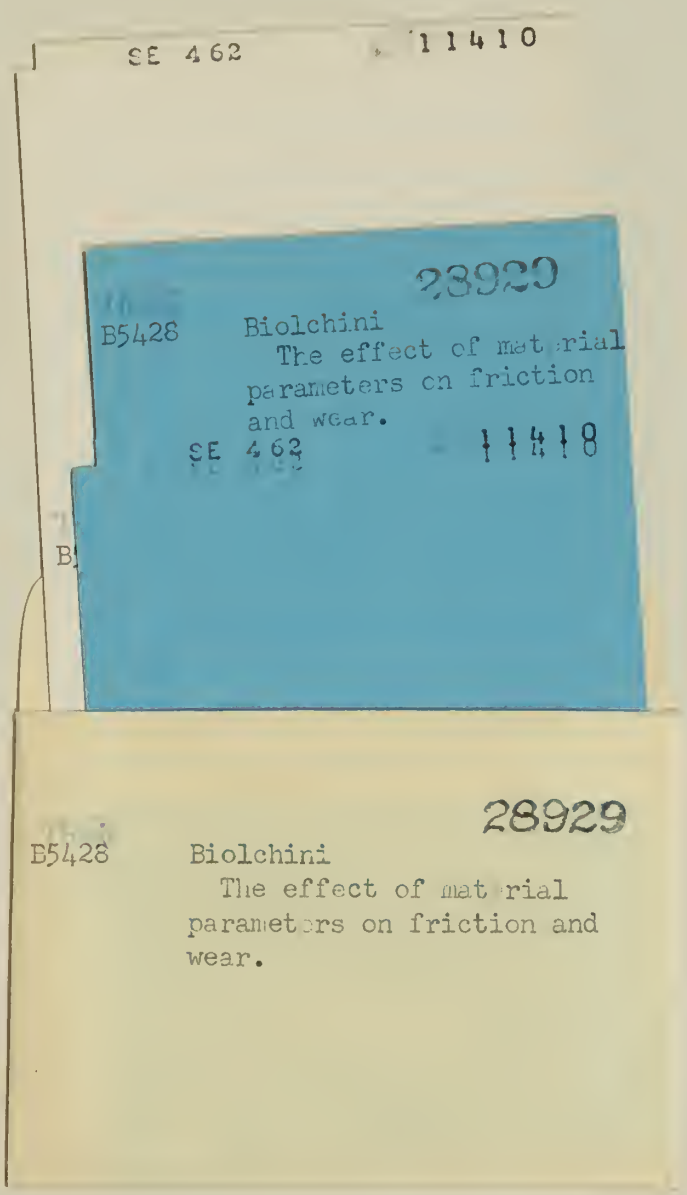
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